Image credit: CVRD (aerial-based imagery) and NHC

Chemainus River Geomorphic Atlas

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Chemainus River Flood Mapping Program

Geomorphic Atlas

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DISCLAIMER

INTRODUCTION

NHC has prepared this document for the Cowichan Valley Regional District (CVRD) to support geomorphic hazard mapping of the potential channel and shoreline migration zones on the Chemainus River floodplain. The geomorphic atlas provides a conceptual framework that can be used to evaluate flood mitigation options.

This atlas provides a summary of NHC's investigation into the geomorphic processes that were used to inform and define the geomorphic hazard mapping, and to provide important context on channel stability and potential future conditions that may affect the geomorphic hazard potential.

SCOPE OF WORK

The study focus is on the geomorphic channel and shoreline migration potential on the Chemainus floodplain and lower approximately 8 km of the Chemainus River. The scope of work does not include an evaluation of sediment sources, terrain assessment, or assessment of the potential or frequency of slope instabilities, debris flow, debris flood, potential for channel jamming and outburst flooding, or hyper-concentrated flow.

ACKNOWLEDGEMENT

We respectfully acknowledge that the Chemainus River, its tributaries, watershed, and estuary lie within the traditional, unceded territories of the Coast Salish Peoples.

The study area falls within the territory of the Hul'qumi'num speaking First Nations peoples, which includes Cowichan Tribes, Halalt, Stz'uminus, Penelakut, Lyackson, and Tsuubaa-asatz Nations .

The following NHC personnel participated in the study:

- Ryan McQueen — Analysis and lead author
- Ilana Klinghoffer — Analysis, co-author, and hazard mapping
- Wil Hilsen — Field investigations, editor, and reviewer

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1 DATA SOURCES

Field Data

- Estuary, river channel, and terrestrial survey data (NHC, May to June 2021)
- Topographic surveys of bank positions and highwater marks (NHC October to November 2021).
- Field photographs (NHC August 2021 to March 2022)
- Mesohabitat spatial data (Cowichan Watershed Board 2021)
- Historical river cross section data (1986 BC Surveys Section, Water Management Branch, BC Ministry of Environment)

Personal Communication and Knowledge Sharing

- Chief James Thomas, Halalt First Nation (7 October 2021)
- Tim Thomas, Halalt First Nation fisheries technician (8 October 2021)
- Halalt First Nation Spill Response Coordinator Geoffrey Backman (9 December 2021)
- Halalt First Nation Band Manager (30 November 2021)
- Penelakut First Nation Band Manager Josh James (30 November 2021)
- Stz'uminus First Nation Council Member and cultural consultant Arthur Jim (18 February 2022) and accompanied by Terry Gibson Stz'uminus First Nation local guide on 18 March 2022).
- Ken Epps, Mosaic Forest Management (17 September 2021)
- Sean Wong, Sr. Biologist. BC Ministry of Transportation and Infrastructure (20 October 2021).
- Jeff Anderson, Geomorphic Consulting (for Cowichan Watershed Board BCSRIF Twin Watersheds Project, 7 March, 2022)
- Dave Clough, DR Clough Consulting (26 October 2021)

Geospatial Data

Imagery

- Historical air photos (1950, 1957, 1968, 1975, 1987, 1992; courtesy of the UBC Geographic Information Centre)
- Google Earth (2005)
- 2019 (MNC) and 2021 (FLNRORD) orthophotos

LiDAR (light detection and ranging) data

- 2019 LiDAR of the Chemainus floodplain (GeoBC)
- 2021 LiDAR of the Chemainus River (Cowichan Watershed Board)

Canadian Hydrographic Service (CHS) Non-Navigational (NONNA) Bathymetric Data

- 10 m grid depth data converted to CGVD2013 elevation data
- Supplemented with CHS Chart3310 data

Basin-scale data sets

- Topography (CDEM)
- ESRI imagery (2019)
- Bedrock geology (BCGS)
- Surface geology (TRIM)
- BC 1:20,000 scale Freshwater Atlas (FWA)

2 APPLICABLE GUIDELINES

The following BC guidelines are applicable:

- Legislated Flood Assessments in a Changing Climate in BC – Professional Practice Guidelines (EGBC, 2018)
- Flood Hazard Area Land Use Management Guidelines (MFLNRORD, 2018)
- Flood Mapping in BC – Professional Practice Guidelines (APEGBC, 2017)

The following guidelines from other jurisdictions have been considered in the undertaking of this study:

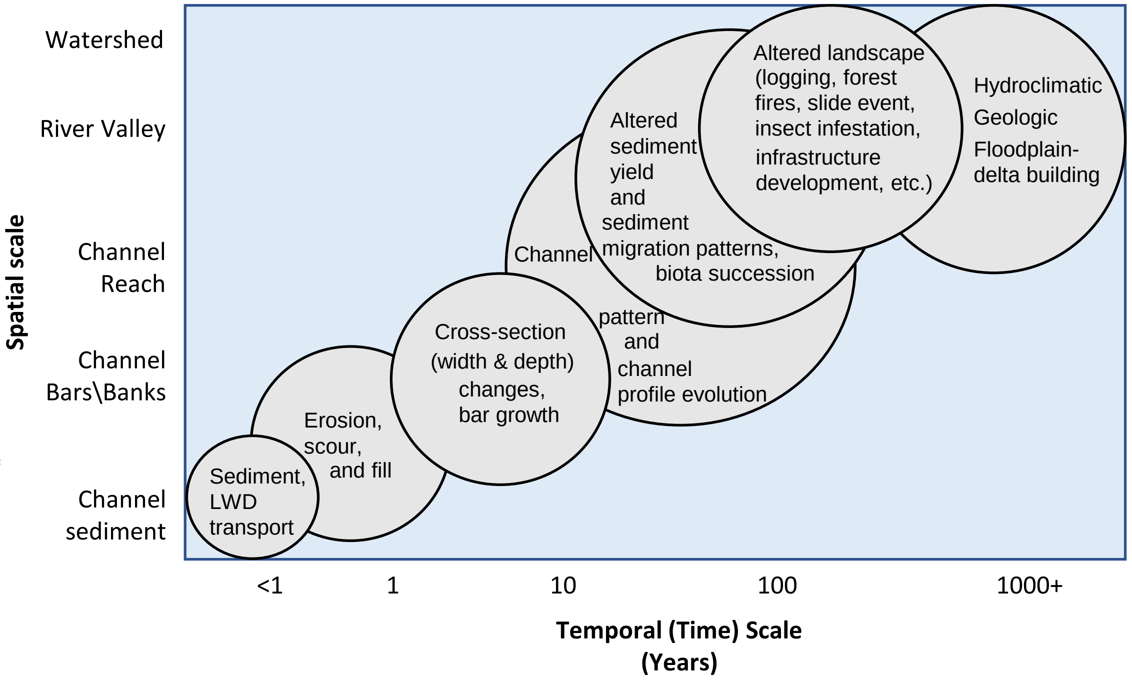
- A Framework for Delineating Channel Migration Zones. Washington State Department of Transportation. Rapp et. al., November 2003.
- Channel Migration Processes and Patterns in Western Washington. A Synthesis for Floodplain Management and Restoration. State of Washington Department of Ecology. Legg et. al., August 2014
- Forest Practices Board Manual. Technical supplement to Washington State forest practice rules. dnr.wa.gov. 2000.

3 CONCEPTUAL FRAMEWORK

The Chemainus River floodplain is prone to hazards associated with channel avulsion, lateral channel instabilities and shoreline erosion. The goal of the hazard mapping conducted for this project is to delineate areas that are susceptible to channel and shoreline migration hazards (Rapp, C.F., Abbe, T.B. 2003). The mapping, referred to herein as a Geomorphic Hazard Map, is intended to help reduce risk by providing guiding information for land use planning.

The following fluvial and coastal processes have been considered in the assessment. These geomorphic processes operate on the landscape at a range of spatial and temporal scales.

- Channel hydraulics associated with floods
- Supply of sediment and large woody debris (LWD) from the watershed and upper channel reaches.
- Channel erosion, scour, and infilling associated with fluvial processes
- Lateral channel instability and channel avulsion potential
- Distributary channel processes and tidal effects
- Shoreline recession associated with wave erosion and sediment transport



▸ Conceptual representation of the different scale of physical influences and fluvial and coastal geomorphic processes operating on the landscape (after Richards et. al. 2002).

The Geomorphic Atlas provides a summary of the field investigations, desktop review and analyses carried out for the study. The document is structured to provide a multi-scaled perspective on the dominant geomorphic processes used to define the mapping units shown in the geomorphic hazard map. These processes are presented in Sections 4 to 9 as summarized below, and Section 10 describes the analysis undertaken for the geomorphic hazard mapping.

- SECTION 4 WATERSHED-SCALE PROCESSES: Describes the present-day hydroclimatic and geologic characteristics of the watershed. Presents an overview level description of the hillslope hazard potential and sediment supply.
- SECTION 5 LAND-USE AND IMPACTS OF EUROPEAN SETTLERS: Identifies major influences and disturbances to the watershed, river system and shoreline. Describes the physical changes that occurred and anticipated longer-term geomorphic response.
- SECTION 6 MODERN VALLEY BOTTOM AND ACTIVE CHANNEL PROCESSES: Defines the modern valley bottom and describes the active channel processes on the Chemainus River floodplain.
- SECTION 7 REACH-SCALE CHANNEL CHARACTERISTICS & DOMINANT PROCESSES: Includes an overview level description of the reach characteristics, and a detailed reach-by-reach summary of key observations, characteristics, and processes.
- SECTION 8 SEDIMENT MOBILITY AND THE CHANNEL PROFILE: Presents study reach-scale longitudinal profile plots of bed elevation and channel changes between 1986 and 2021, based on a comparison of survey data. Includes longitudinal profile plots of sediment grain size characteristics, and sediment mobility potential.
- SECTION 9 FUTURE CONDITIONS: Description of potential future conditions and geomorphic response:
  - Watershed-scale or river valley-scale changes that may physically change the landscape and induce a longer-term geomorphic response under present-day or future hydroclimatic conditions. The geomorphic response to some historical watershed-scale changes (e.g., logging, road and rail development, historical mining) are ongoing.
  - Altered flow regime and reach-scale and channel-form adjustments.
  - Base level changes, landward migration of tidal and coastal effects, and adjustments to the channel profile.

4 WATERSHED SCALE PROCESSES

Physiography and Watershed Morphometrics

The Chemainus River Watershed is located on the east coast of Vancouver Island, draining an area of 385 km^2. At 1,500 m above sea level, Mount Whymper is the highest point in the watershed.

In the upper watershed, the river flows southeast and turns northeast near Mount Sicker, parallel to a fault line, and onto the Nanaimo Lowlands (Yorath and Nasmith, 1995). The channel was originally formed by glaciofluvial processes, and the present-day channel is underfit and is confined by tall channel banks. As the river erodes the toe of these banks, steeper sections become prone to failures and provide an important source of sediment to downstream reaches.

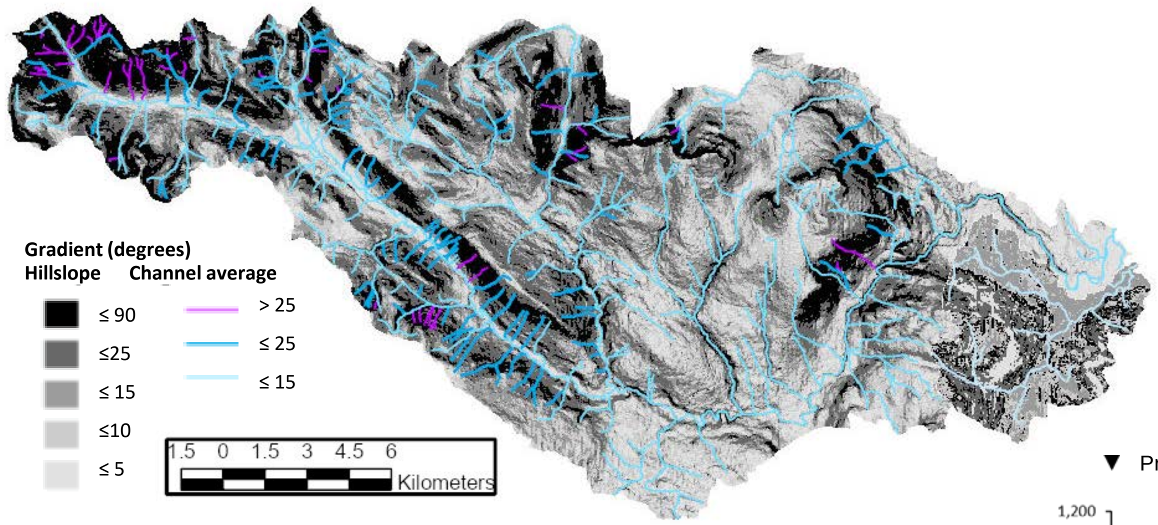
About 8 km from the mouth, the Chemainus River exits confinement and continues onto a broad alluvial plain. Here, the channel exhibits an irregularly sinuous meandering planform, whereby the position of meander bends are confined by bedrock outcrops, bridge constrictions and rock armoured banks.

The morphometric analysis indicates clearwater floods are likely to be the dominant hydrogeomorphic processes on the mainstem channel of the lower Chemainus River, though smaller tributary sub-basins in the upper watershed may be prone debris flows and debris floods.

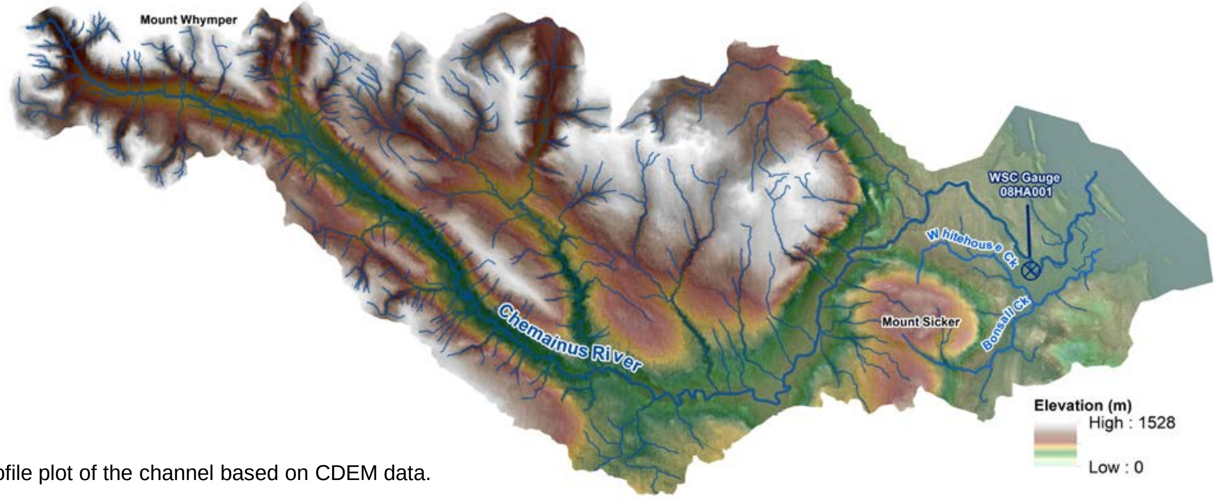
Watershed morphometrics are typically used to conduct a preliminary assessment whether a watershed is dominated by clearwater floods, debris floods or debris flows (Church and Jakob, 2020; Wilford et al., 2004).

Morphometric parameters evaluated for this study include watershed area and length, relief ratio, and the Melton ratio (the ratio between basin relief and the square root of the basin area).

Watershed Morphometrics	
Watershed Area (km^2)	384.6
Watershed Length (km)	38.0
Melton Ratio	0.08
Relief Ratio	0.04

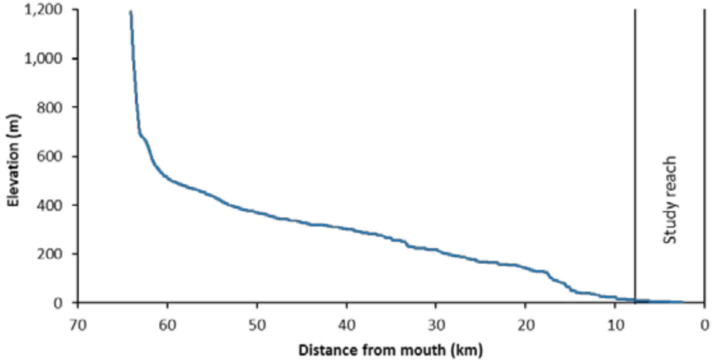


▲ Channel average and hillslope gradients (CDEM and FWA data).



▲ Watershed basin plot developed using CDEM and FWA data.

▼ Profile plot of the channel based on CDEM data.



High energy hydrogeomorphic hazards – debris flows and debris floods – can entrain substantial volumes of sediment and woody debris, producing a peak discharge much larger than a typical flood event; debris flows may occur in channels that have an average slope ≥15 degrees (APEGBC, 2017). Hillslope gradients ≥25 degrees are considered to have a potential for instabilities (Sidle et. al, 1985).

Based on the CDEM data, approximately 27% of the Chemainus River watershed is >15 degrees and 18% is >25 degrees (shown in the grey and black shading above). Dark blue and purple channels show tributary channels prone to debris flows.

The channel profile upstream of the study reach becomes steeper and includes several falls.

- Between 20 km to 60 km upstream of the mouth the average mainstem channel gradient is approximately 0.9% (~0.5°)
- In the upper 4 km it steepens to approximately 17% gradient (~9.7°).

4 WATERSHED SCALE PROCESSES

Climate and Hydrology

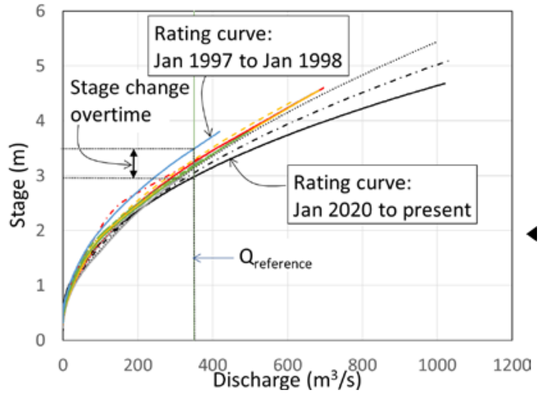
- The Chemainus River Watershed resides within the Eastern Vancouver Island hydrologic zone (Obedkoff, 2003).
- The discharge regime closely follows the precipitation regime. Most rainfall occurs in the winter, with November being the wettest month, and July the driest.

Based on studies in northeast Vancouver Island and the Sunshine Coast, rain dominated zones extend up to 300 m elevation and the transient snow zone is between 300 to 800 m, with the snowpack zone above 800 m. (Babakaiff, 2000). Based on a hypsometric analysis, the proportion of the watershed within each zone is presented below:

- Rain dominated : approximately 13%
- Transient snow zone: approximately 59%
- Snowpack zone: approximately 28%

The Water Survey of Canada (WSC) gauge 08HA001 is installed near Highway 1 along the lower reach of the river (see Page 3 for gauge location).

- Hydraulic model results conducted for this study indicate that up to 30% of the river's flow spills overbank upstream of the gauging station during flood events, and therefore peak flood discharges reported by WSC may be under-estimated.
- Observations indicate relative water levels (i.e., stage) associated with the $Q_{reference}$ have fluctuated by more than 0. 5 m between 1995 and present. This relative change in stage infers a correspondingly similar magnitude of channel bed fluctuation.



◄ Stage-discharge relationship for WSC hydrometric station Chemainus River near Westholme (08HA001) since 1995

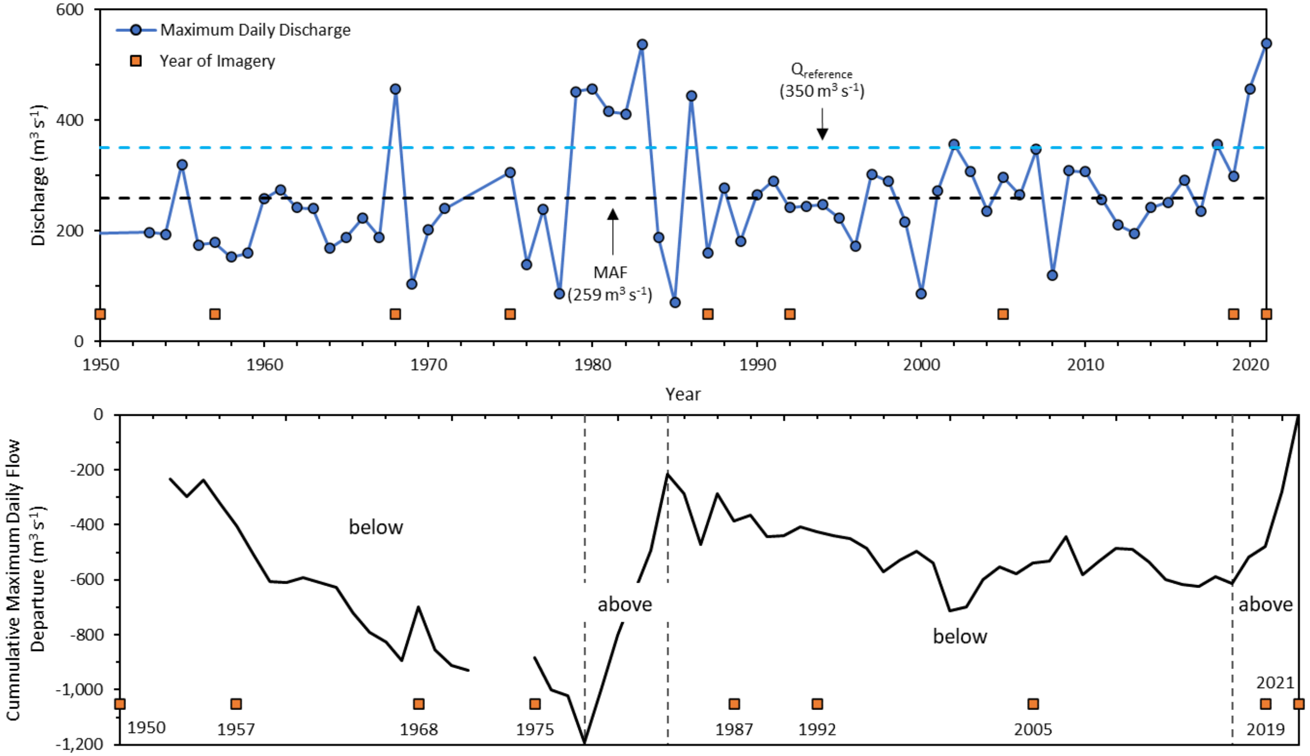
This study analyzes geomorphic processes using a reference discharge ($Q_{reference}$) of 350 $m^3 s^{-1}$. This value approximates the bankfull discharge, the flood condition at which the active channel width is inundated with water and coarse bed sediment is likely to be mobilized. This value has been applied to estimate sediment transport potential and sediment transport processes at a broad reach-scale, and more detailed analysis could help refine the critical discharge value for sediment entrainment.

The largest floods within the period of record (1950 to 2021) occurred in 2021, 1983, 2020, 1980, and 1968 (in rank order from largest event).

Recognizable periods of above average floods occurred from 1978 to 1983 and from 2017 to 2021. Below average floods dominated other time periods with occasional years that experienced a large flood event.

The record of cumulative maximum daily flows notably plots below the cumulative long-term average, whereas a system in equilibrium would tend to vary above and below the average.

The reason for this is that high flows occurring from 2018 to 2021 are substantially greater than in prior years, which skews the long-term average towards these more recent events. This may imply that the system is shifting to a new equilibrium state in which higher magnitude floods occur more frequently.



▲ Upper graph: Historical annual maximum daily flow sequence from the WSC gauge 08HA001 on the Chemainus River. MAF = mean annual flood.

Lower graph: Cumulative flood flow departures showing trends in peak daily flows relative to the long-term average (i.e., where the cumulative maximum daily flow departure equals 0).

A rising trend indicates a time period with floods that are persistently above the average annual, whilst a falling trend indicates a time period with floods that are persistently below average. Orange squares represent years of available air photos or orthophotos that were used to interpret channel changes over time.

4 WATERSHED SCALE PROCESSES

Bedrock Geology

The Chemainus River Watershed lies within the Wrangellia terrane, which on Vancouver Island comprises three volcano-sedimentary cycles (Paleozoic Sicker Group, Upper Triassic Vancouver Group and Jurassic Bonanza Group) overlapped by Upper Cretaceous sediments of the Nanaimo Group (Massey and Friday, 1987).

Rocks of the Island Plutonic Suite are relatively stable and resistant to weathering processes leading to relatively lower landslide rates than other lithologies (Guthrie, 2005). This may not hold true for areas where logging is involved. Conversely, rocks of the Sicker group are more vulnerable to landslides (Guthrie, 2005).

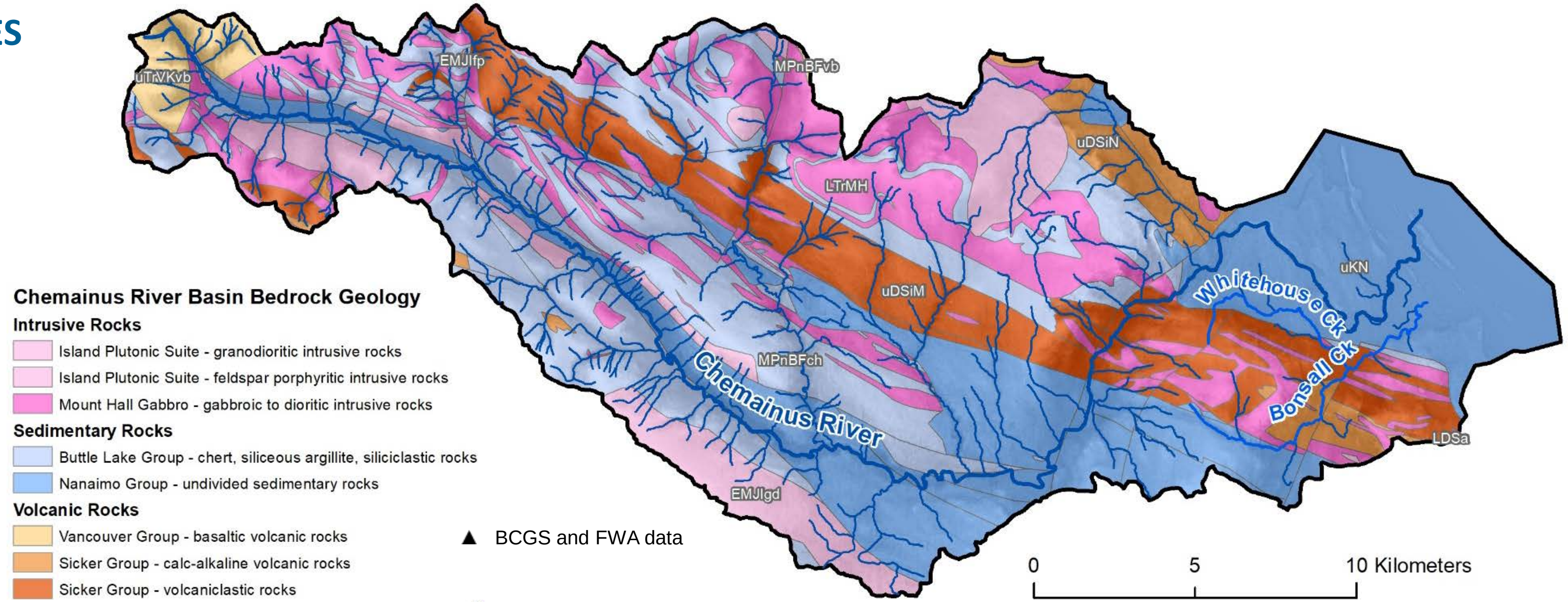
Surficial Geology

The watershed is covered by a blanket of till, with colluvial deposits accumulating on steep hillslopes.

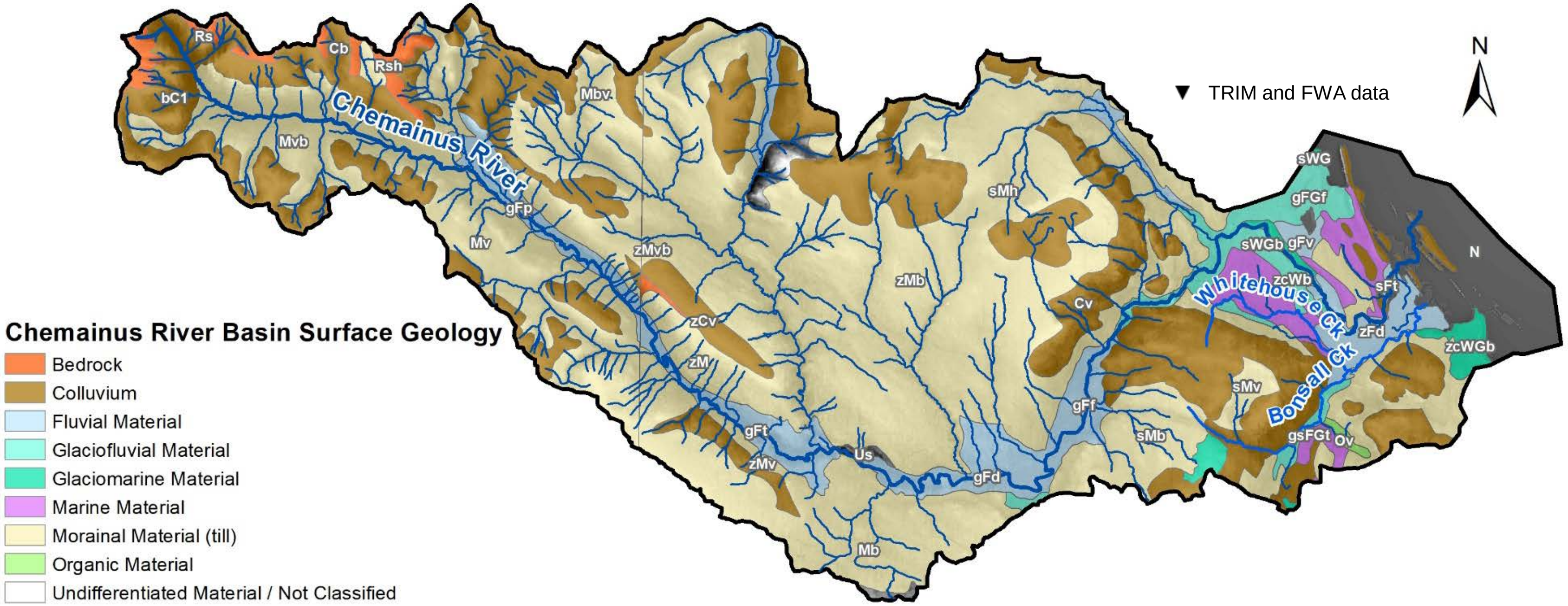
Striae, flutings, and stoss and lee topography indicate that ice moved in a south to southeast direction during the last major sheet that occupied Vancouver Island (Halstead, 1966).

In the lower watershed, the modern-day channel is underfit and incises into glaciofluvial deposits. The lower 10 km or so of the river is bordered by marine and glaciomarine deposits that form high terrace bluffs, partially constraining the position of the modern-day channel.

▲ Terrace bluffs in the lower watershed composed of compact glaciomarine sediment.



▲ BCGS and FWA data



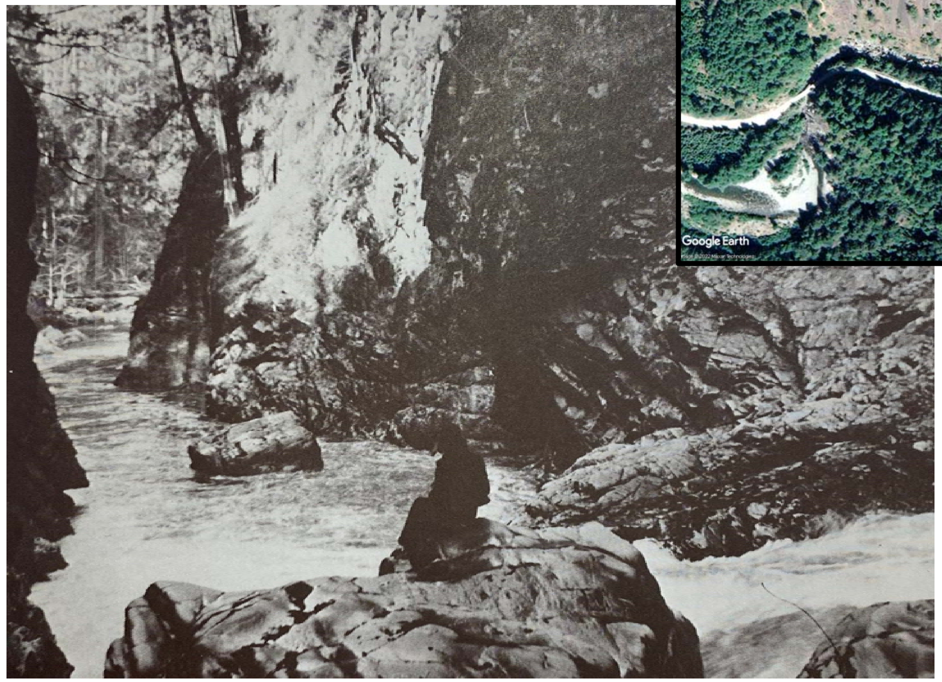
▼ TRIM and FWA data

Sediment Supply Potential

Sediment supply The rate of sediment supply to the lower reach partly depends on hillslope erosion processes that deliver sediment to the channel system farther up in the watershed. There is a recognized potential for instabilities in the watershed (described in more detail on Page 3).

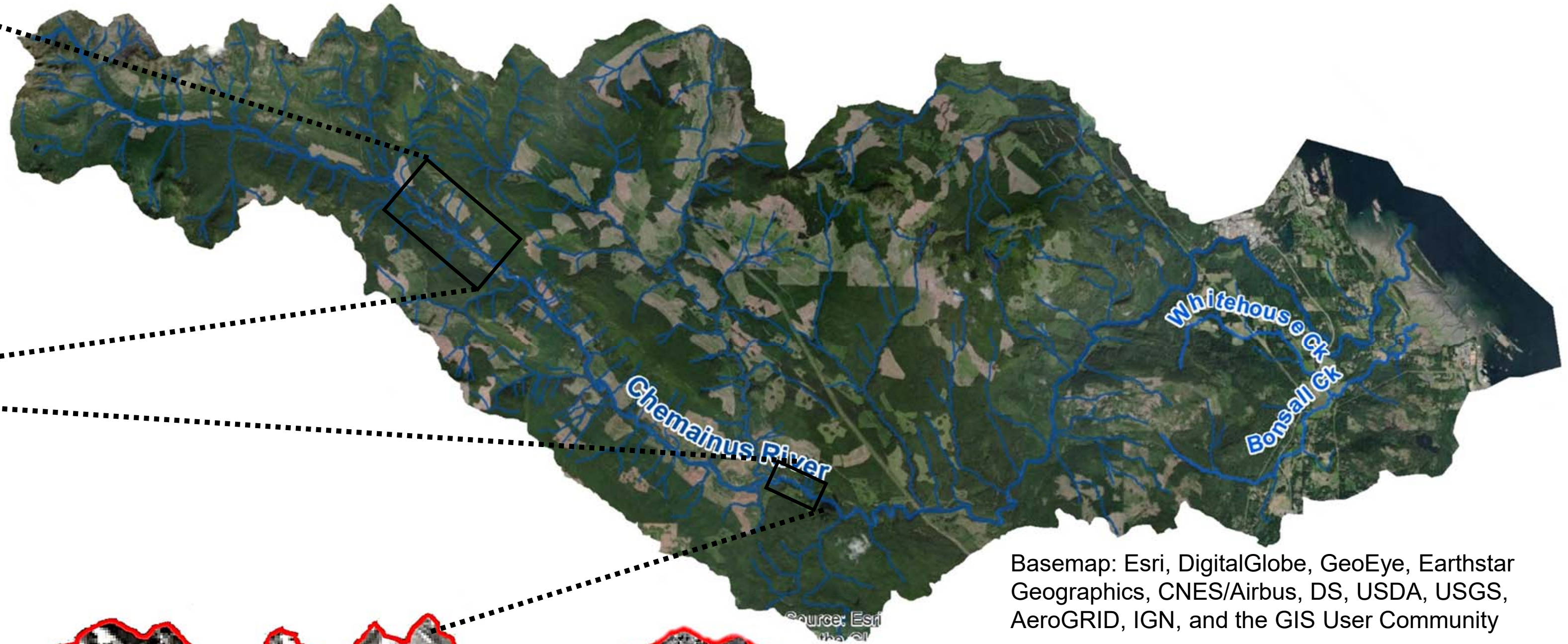
Bank erosion and slope failures along the channel banks supply sediment to the mainstem.

Altered forest cover affects snow accumulation, and melting, interception and transpiration of precipitation during storms (Pike et. al. 2010). Hydrologic recovery occurs with forest regeneration; however, the geomorphic response to logging is a more complex and longer-term process (see Page 34).

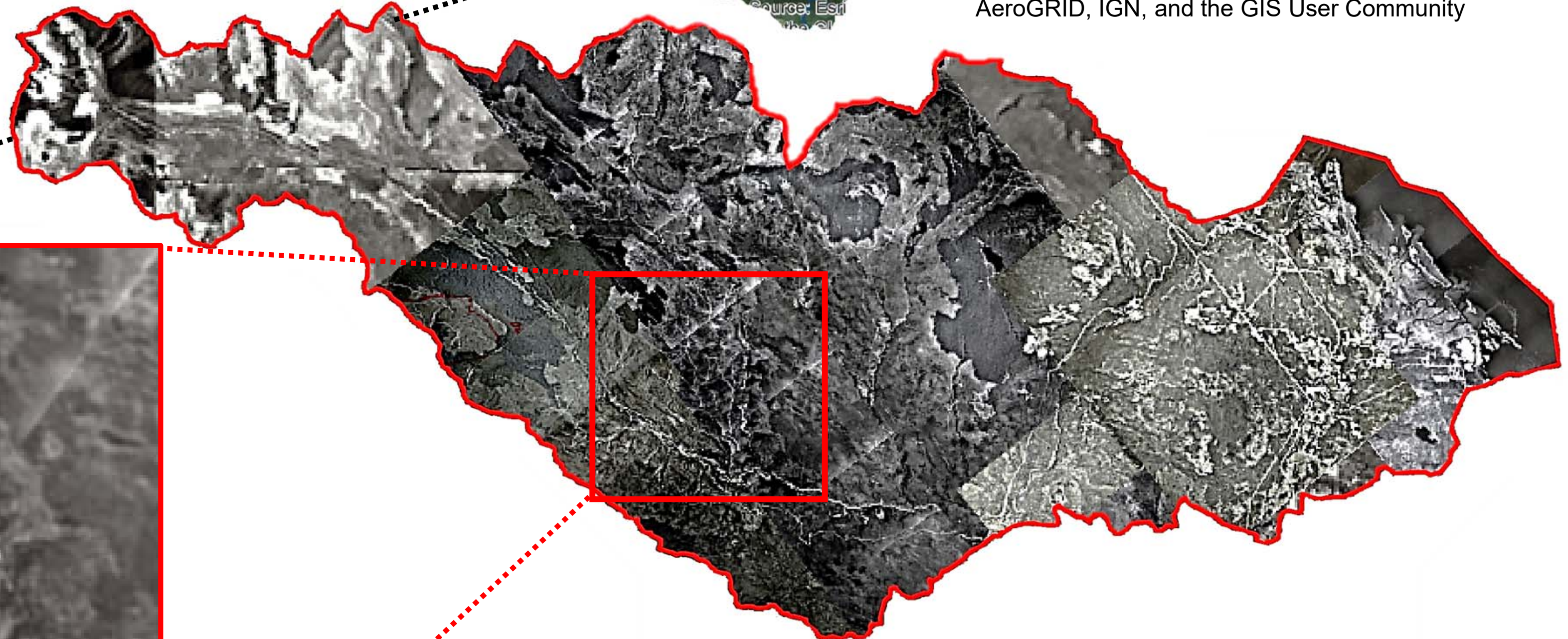


▲ Copper Canyon at the falls (Olsen, W.H., 1981), reportedly the narrowest location on the Chemainus River. Steep, narrow canyons in the upper watershed create a potential for channel blockages.

▼ Recent image of the watershed forest cover area. Inset image at the top left illustrates an unstable channel reach in the upper watershed that is a sediment supply source. The image at bottom left shows slope failures along a steep stream bank located within a confined channel reach, also a noticeable source of sediment.



Basemap: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus, DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community



▲ Overtime, logging has occurred in much of the watershed. The image above is compiled from historical air photo (primarily circa 1962 with supplemental, lower resolution 1987 imagery to infill gaps in the photo record). Large cut blocks are visible on relatively steep terrain areas. Visible slide paths lead into the channel in the historical photo records.

5 LAND USE AND INFLUENCE OF EUROPEAN SETTLERS

The Chemainus River, its watershed, estuary, and surrounding islands have been used since time immemorial by First Nation peoples for village sites, hunting, fishing, trapping, harvesting, and other cultural and sacred purposes (Rozen DL, 1985; Arthur Jim, Stz'uminus First Nation Band Council member and cultural consultant, pers. comm. 18 March 2022).

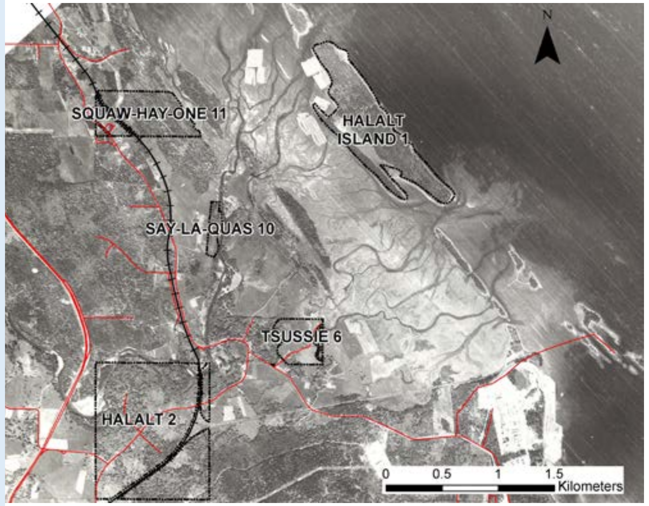
Geomorphic response to European settlers

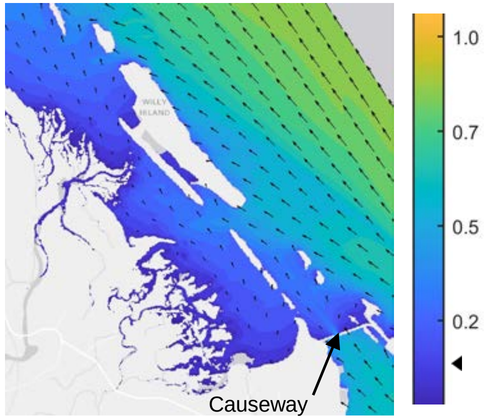
European settlement has dramatically altered the Chemainus River, and its watershed, floodplain, estuary, and coastline. This includes:

- Altered sediment yield and timing and frequency of peak flood events associated with historical mining activities and legacy forestry.
- Altered drainage patterns and potential for hillslope instabilities and sedimentation associated with the legacy road deactivation practices and development of cutblocks and road and rail networks in the watershed. Ongoing forestry practices in the watershed have not been evaluated for this study.
- Altered sediment deposition patterns, and channel planform and profile changes associated with channel hydraulics at road and railway bridge crossings.
- Encroachment into historical channel migration zones.
- Concentration of channel flow during food events associated with the earthen berm constructed along the southern bank of the floodplain upstream of Highway 1.
- Altered channel flow pathways and floodplain flow resistance associated with land clearing and landscaping in support of agriculture and other intensive land uses on the floodplain.
- Altered rates and patterns of deposition of sediment and LWD in the low gradient channel reaches, in the distributary channel zone and in the estuary (Chief James Thomas, pers. comm. 7 October 2021).
- Altered tidal and wave processes in the estuary associated with the construction of the causeway to the pulp and paper mill.

▲ Top photo: Historical logging operations in the Chemainus River watershed. Bottom photo: First bridge over Chemainus River. (Copper Canyon Commemorative Committee, 1990).

▼ 1962 air photo overlain with road and railway networks that bisect the Chemainus River floodplain, interrupting natural drainage patterns, and cutting off former distributary channels and occasionally active fluvial zones.





◀ SWaN model simulations for an easterly storm, showing simulated wave height (m) and wave direction. The results show a pronounced influence of the pulp mill causeway on wave propagation into and out of the estuary.

▲ Google Earth image showing two water wells (white circles) located within the active channel corridor.

- In 1862, J.D. Pemberton, Surveyor-General reported that, *"the river has cut perpendicular passes through clay hills. High on the brink stand pines weighing 10 to 40 tons, which with every fresh landslip are swept with great velocity down the stream. Below these hills the river could not well be bridged"* (Olsen, W.H., 1981).
- Industrial development reportedly had started as early as 1866 and expanded with establishment of the Esquimalt and Nanaimo Railway in 1886. Harvest cut blocks and other development associated with logging has altered sediment supply rates into the Chemainus River and estuary, compared to pre-disturbance conditions. Development of the Crofton pulp mill in 1958 has closed off the southern opening to the estuary between Vancouver Island and Shoal Island (Bell, L.M., Kallman, R.J., 1976).
- By the 1900s the Chemainus River was spanned by a concrete and steel bridge to replace a wooden truss structure (Turner R.D. 1973).
- The Federal Government enacted fish licensing regulations is 1888, and by 1913 the Department of Fisheries and Oceans forcibly removed all First Nations fishing weirs from the Cowichan and Chemainus Rivers. (Hodding, B.A 1998).
- In the 1930s and 1940s, development of the Copper Canyon mine and the growing logging industry was supported by the construction of a 63 km long railway line by the Victoria Lumber Company Ltd.

6 MODERN VALLEY BOTTOM AND ACTIVE CHANNEL PROCESSES

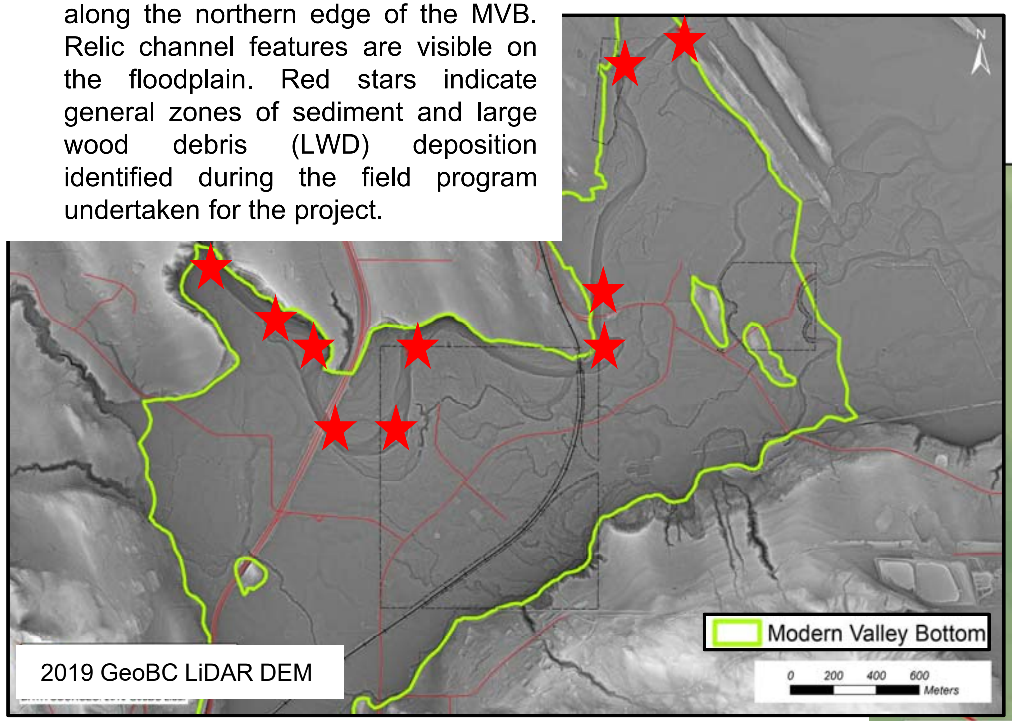
The Modern Valley Bottom (MVB) is the portion of the landscape that has been affected by channel processes under the contemporary hydroclimatic regime (Olsen et al. 2014).

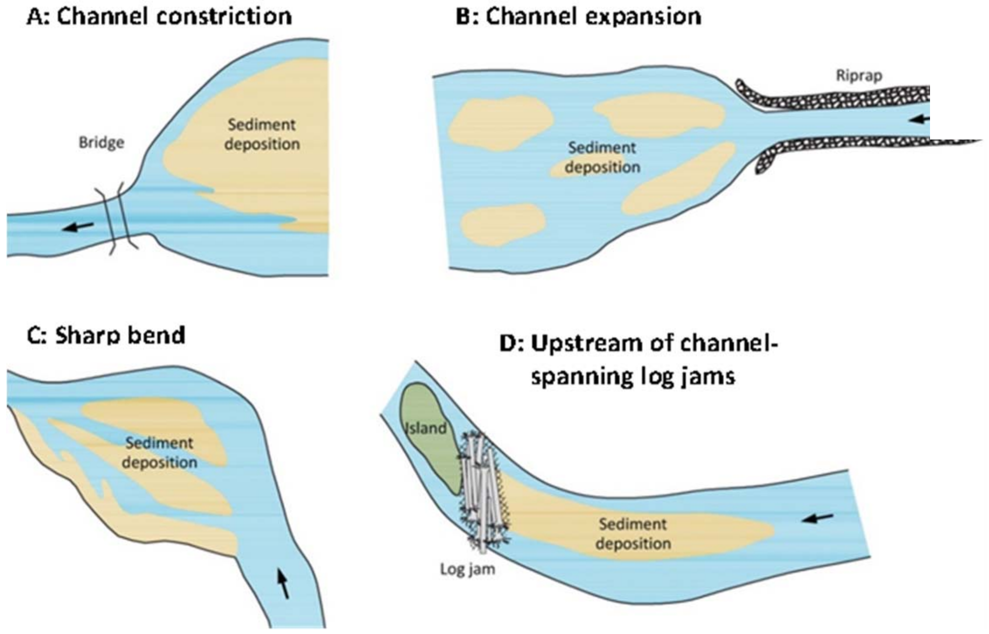
The MVB is a defined region that is based on interpretation of relict fluvial features, bedrock and surficial geology, and relative elevations on the valley landscape.

The Chemainus River MVB includes areas that are potentially susceptible to active channel processes, including lateral channel shifting and channel avulsion. A channel avulsion is a process whereby a channel is diverted from an established channel to a new channel path (First-order Avulsion) or pre-existing path (Second-order Avulsion) on the floodplain.

Channel processes that can trigger an avulsion include the formation of log jams or other blockages and accumulation of sediment in depositional zones.

▼ The texturized DEM of the floodplain. The present-day active channel flows along the northern edge of the MVB. Relic channel features are visible on the floodplain. Red stars indicate general zones of sediment and large wood debris (LWD) deposition identified during the field program undertaken for the project.



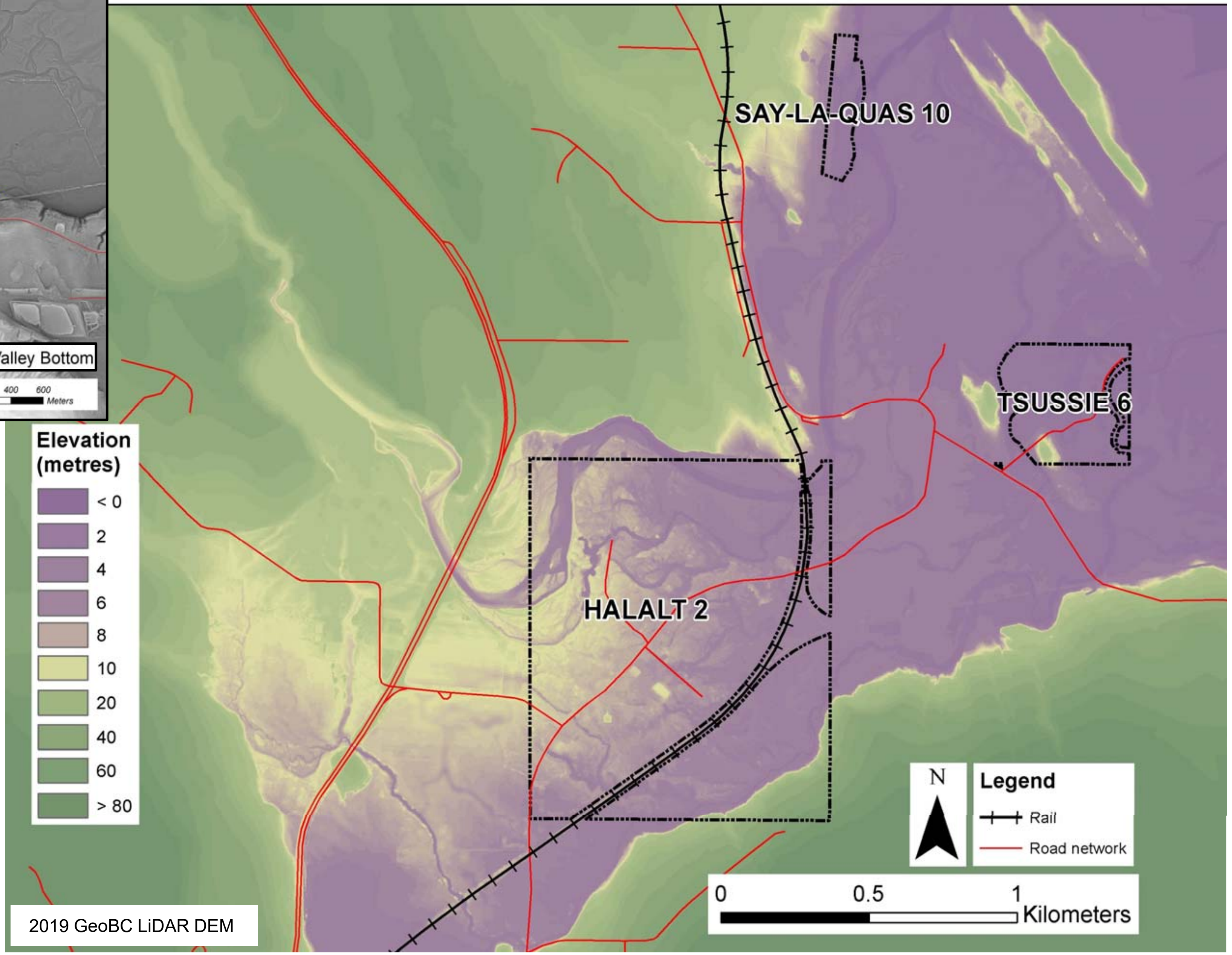


◀ The schematic at left (after NHC, 2015a) illustrates discrete locations where sediment conceptually is more prone to depositing along a stream channel.

In general, sediment tends to deposit along the Chemainus River channel at specific locations.

- Upstream or downstream of channel constrictions (A, B).
- Along the outside of meander bends (C).
- Upstream of backwatered areas that can form as a result of channel obstructions such as log jams (D) or in tidally influenced areas.

▼ At the upstream end of the MVB floodplain, the Chemainus River flows onto an alluvial fan. The fan is characterized by a radial topographic pattern emanating from valley confinement onto the floodplain. Distributary channels are common on fan formations (Rapp et. al. November 2003). The MVB is defined by the steep sided valley walls (illustrated by the relatively dark green colour shades in the figure below). The alluvial fan is illustrated by the transitional light green, yellow and light purple colours between the valley walls and floodplain.



7 REACH-SCALE CHANNEL CHARACTERISTICS AND DOMINANT PROCESSES

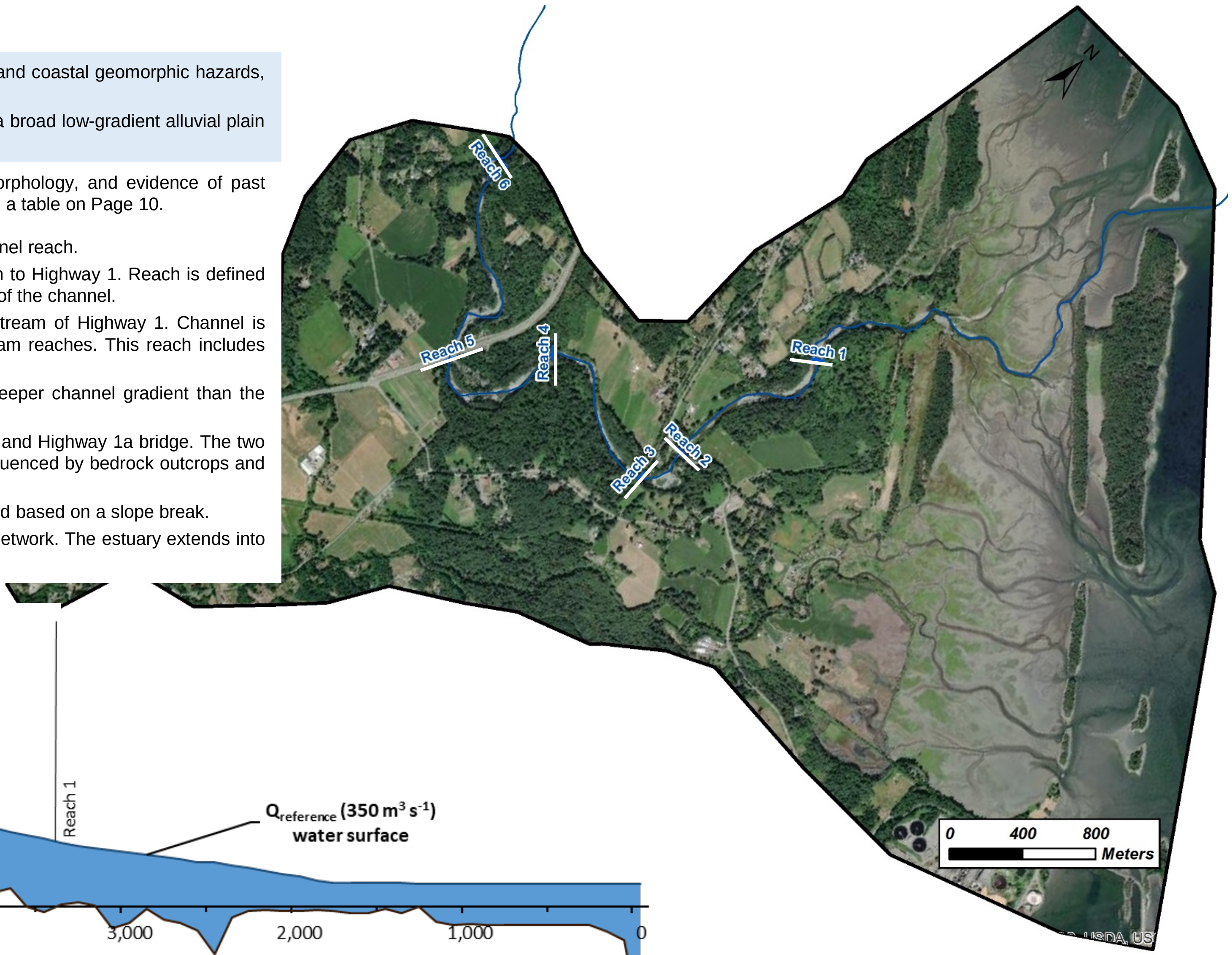
Study Extent

The lower approximately 8 kilometers of the Chemainus River were mapped for channel migration and coastal geomorphic hazards, matching the approximate extent of hydraulic modeling used to define flood hazard maps.

Within the mapped area, the Chemainus river exits a confined canyon reach and spreads out onto a broad low-gradient alluvial plain upstream of an estuarine environment where the Chemainus River meets the ocean.

The study area was subdivided into reaches based on differences in channel hydraulics and morphology, and evidence of past channel migration and lateral instability. Criteria used to discretize channel reaches are summarized in a table on Page 10.

- **Reach 7:** (upstream of the hydraulic model extents) encompasses a steep, confined channel reach.
- **Reach 6:** extends from the transition from a confined to unconfined channel downstream to Highway 1. Reach is defined by a relatively stable channel planform constrained by a high terrace along the north side of the channel.
- **Reach 5:** a zone of hydraulic expansion (and a depositional zone) immediately downstream of Highway 1. Channel is laterally unstable and has a lower degree of confinement than upstream and downstream reaches. This reach includes numerous intermittent flood channels.
- **Reach 4:** confined by a terrace on the north side of the channel. This reach has a steeper channel gradient than the upstream and downstream reaches.
- **Reach 3:** sediment and log debris depositional zone located between the railroad bridge and Highway 1a bridge. The two crossings form a distinctive hydraulic control on the system. This reach is also heavily influenced by bedrock outcrops and a rock armoured southeastern embankment.
- **Reach 2:** located downstream of the Highway 1a bridge. The downstream extent is defined based on a slope break.
- **Reach 1:** encompasses the relatively flat reach, characterized by a distributary channel network. The estuary extends into the Stuart Channel.



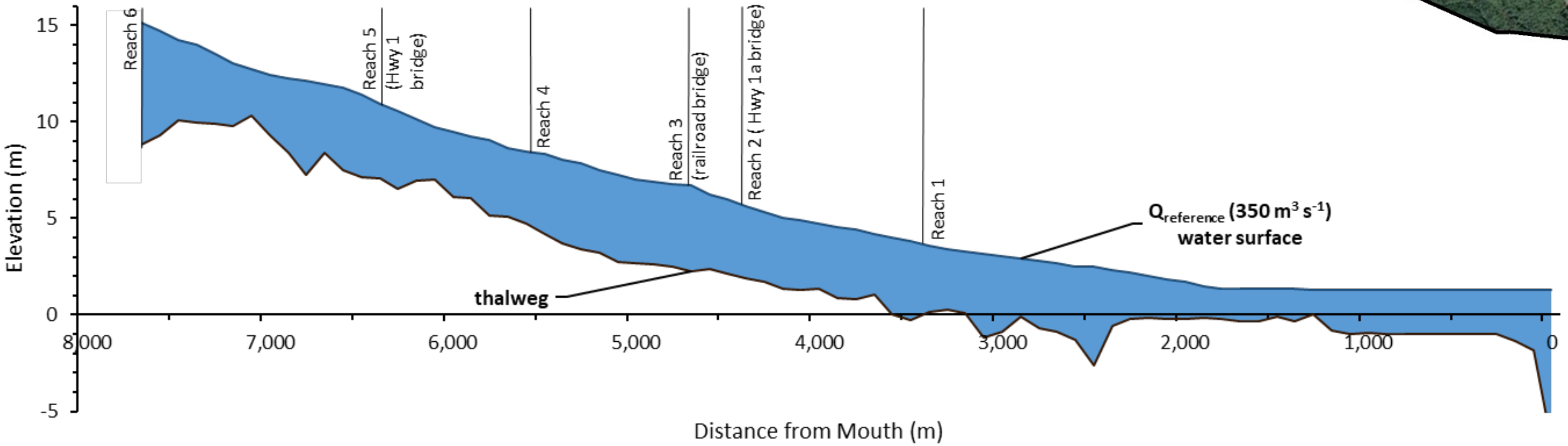


Image source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus, DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community)

7 REACH-SCALE CHANNEL CHARACTERISTICS AND DOMINANT PROCESSES

Reach-Scale Channel Characteristics

Parameter	Description	Units	Reach 7	Reach 6	Reach 5	Reach 4	Reach 3	Reach 2	Reach 1
Streamwise Length	Streamwise length of the reach	m	1,217	1,415	813	937	296	996	3,327
Straight-Line Length	Straight-line length of the reach	m	1,133	1,132	570	827	264	895	2,327
Sinuosity Ratio	Ratio of stream length to straight-line length	$m\ m^{-1}$	1.07	1.25	1.43	1.13	1.12	1.11	1.43
Channel Type	Channel type as defined by the sinuosity ratio	-	straight	sinuous	sinuous	sinuous	sinuous	sinuous	sinuous
Down-valley slope to channel slope ratio	Valley slope divided by streamwise channel slope	$m\ m^{-1}$	1.06	1.15	1.84	2.11	1.32	2.32	4.73
Bankfull Width	Reach-average channel width (2021)	m	37	80	114	43	65	44	65
Bankfull Width to Depth Ratio	Wetted width to depth ratio at bankfull conditions	$m\ m^{-1}$	-	22.1	34.2	9.9	16.9	12.1	18.8
$Q_{reference}$ - Average Shear Stress	Reach-averaged shear stress from 2D modeling of the approximate bankfull discharge (i.e., $Q_{reference}$)	Pa	-	82	87	64	95	46	18
$Q_{reference}$ - Maximum Shear Stress	Maximum shear stress from 2D modeling of the approximate bankfull discharge (i.e., $Q_{reference}$)	Pa	-	177	135	109	124	68	41
Grain Size - D_{50}	Median size of surface sediment	mm	-	51	38	34	33	-	16
Grain Size - D_{84}	84th percentile size of surface sediment	mm	-	86	68	58	59	-	28
Unvegetated Bar Area	Unvegetated bar area mapped from 2021 orthophoto	m^2	5,502	18,284	17,462	3,685	5,888	9,523	14,613
Vegetated Bar and Island Area	Vegetated bar and island area mapped from 2021 orthophoto	m^2	-	17,176	27,146	6,215	4,559	6,285	5,316
Average Erosion Rate	Reach-average erosion rate from 1950 to 2021, based on bankline delineation interpreted from available imagery (2021 imagery taken prior to flood)	$m\ yr^{-1}$	-	0.4	0.9	0.7	0.7	0.8	-
Maximum Erosion Rate	Maximum erosion rate from 1950 to 2021, based on bankline delineation interpreted from available imagery (2021 imagery taken prior to flood)	$m\ yr^{-1}$	-	1.3	7.1[1]	1.4	4.5	2.0	-
Number of Log Jams	Number of log jams identified by Cowichan Watershed Board (2021)	-	4	13	14	7	6	10	33
Identified Historical Avulsions	The number of avulsion events identified from 1950 to 2021 aerial imagery and historical maps from the 1800s.	-	0	0	1	1	0	1	Many

Notes:

1. In Reach 5, the Maximum Erosion Rate was calculated in two different ways based on the location within the reach and available information. Along the left bank and along the downstream portion of the right bank, the Maximum Erosion Rate of 0.9 $m\ yr^{-1}$ was calculated using the same procedure used for the other reaches, based on air photo bankline delineation from 1950 to 2021. Along the upstream portion of the right bank, from RKM 5.9 to 6.4, recent survey data showing evidence of erosion associated with the November 2021 flood was available. This additional survey information was used in calculating a Maximum Erosion Rate of 7.1 $m\ yr^{-1}$ for the right bank along this segment of the channel.

nhc

Channel Assessment Meso-habitat Spatial Data (Cowichan Watershed Board 2021)

As part of a detailed channel assessment carried out in the summer of 2021 (Cowichan Watershed Board, 2021), spatial meso-habitat data was made available for this project. This dataset included: bankfull width to depth ratio, channel entrenchment, complexity, disturbance, floodplain availability, geomorphic condition, mesohabitat, spawning gravels, stream cover, stream incision, stream substrates, wetted width to depth ratio, and log jams.

Reach breaks (RBs) within the study area, as defined by the Cowichan Watershed Board (2021) data, are also illustrated in the map to the right and summarized below. These reach breaks extend upstream through the entire 64 km length of the channel, and so the study area is more broadly divided into three reaches, based on differences in channel morphology/confinement and tidal influence.

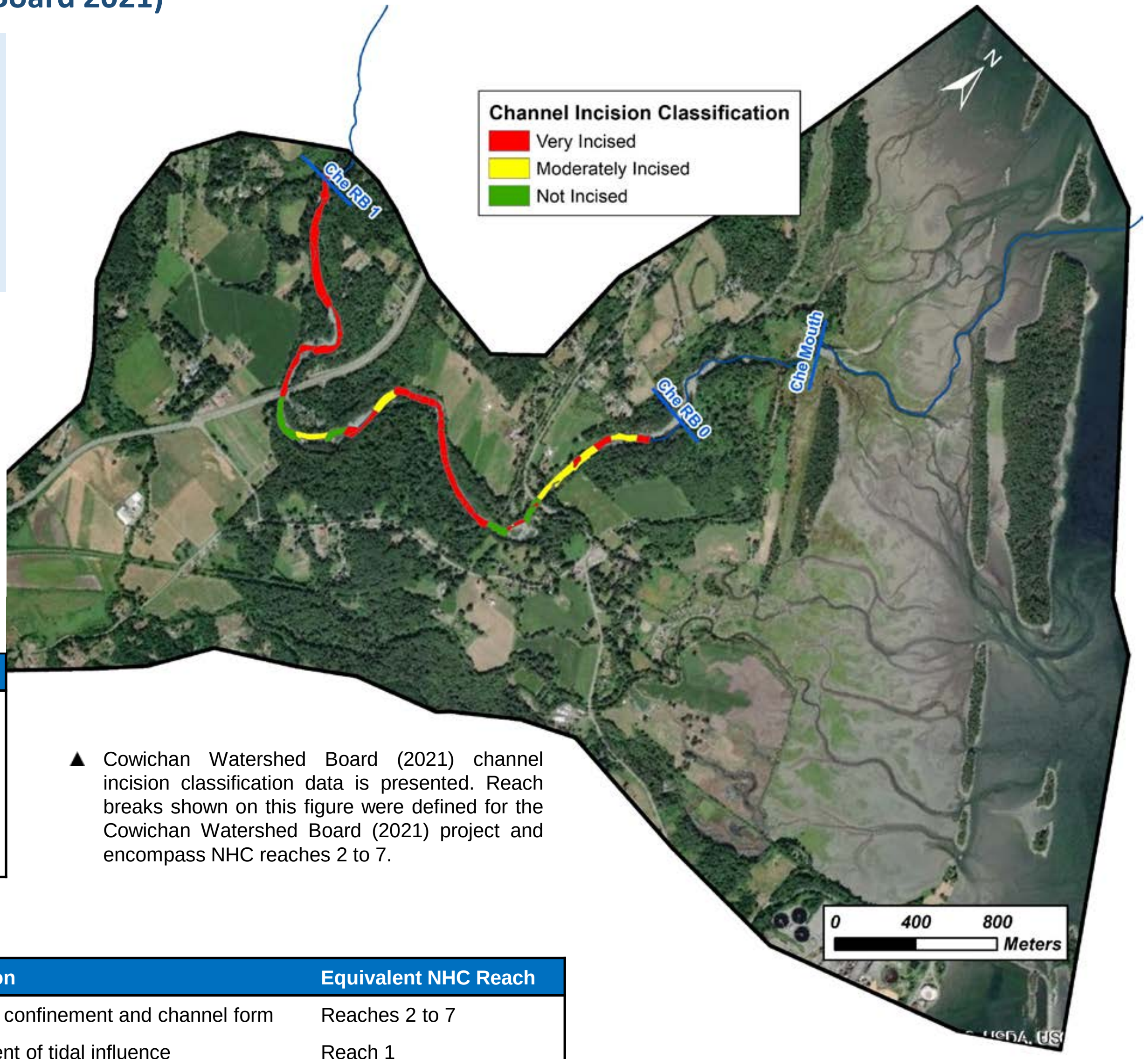
Channel Sinuosity and Avulsion Potential

Cowichan Watershed Board (2021) Reach 1 (RB 1) encompasses NHC's reaches 2 to 7 and broadly incorporates the Chemainus River reach between the confined valley and tidally influenced zone.

This reach has a sinuosity ratio of 2.0 which is reflective of a 'meandering' channel type and indicative of a channel that has a higher propensity to avulse during a high-discharge event. Typically, avulsions occur when the channel sinuosity is greater than 1.5, assuming the discharge exceeds the threshold needed for an avulsion (Forest Practices Board, 2004).

This sinuosity computed based on the Cowichan Watershed Board (2021) reach is higher than the shorter reaches that NHC used for the erosion rate classification calculations. This highlights the scale-dependent nature of this parameter. Application of the Watershed Board (2021) reach evaluates channel and floodplain morphology at the valley-scale, which is considered appropriate for evaluating channel avulsion potential.

Parameter	Description	Units	RB 1	RB 0	Che Mouth
Streamwise Length	Streamwise length of the reach	m	4,260	984	2,470
Straight-Line Length	Straight-line length of the reach	m	2,127	792	1,750
Sinuosity Ratio	Ratio of stream length to straight-line length	$m\ m^{-1}$	2.00	1.24	1.41
Channel Type	Channel type as defined by the sinuosity ratio	-	meandering	sinuous	sinuous
Channel Slope	Reach-average slope along the thalweg	$m\ m^{-1}$	0.0020	0.0023	0.0017



▲ Cowichan Watershed Board (2021) channel incision classification data is presented. Reach breaks shown on this figure were defined for the Cowichan Watershed Board (2021) project and encompass NHC reaches 2 to 7.

Channel Incision

Channel incision is a metric used to describe the degree of connectivity between the stream and adjacent floodplain. Very incised areas are considered relatively more disconnected from the floodplain, whereas areas that are classified as not incised are relatively more connected to the floodplain.

Note: thalweg refers to the line connecting the deepest part of the channel profile

RB Name	Description	Equivalent NHC Reach
RB 1	Change of confinement and channel form	Reaches 2 to 7
RB 0	Upper extent of tidal influence	Reach 1
Che Mouth	Mouth of Chemainus main channel	Reach 1

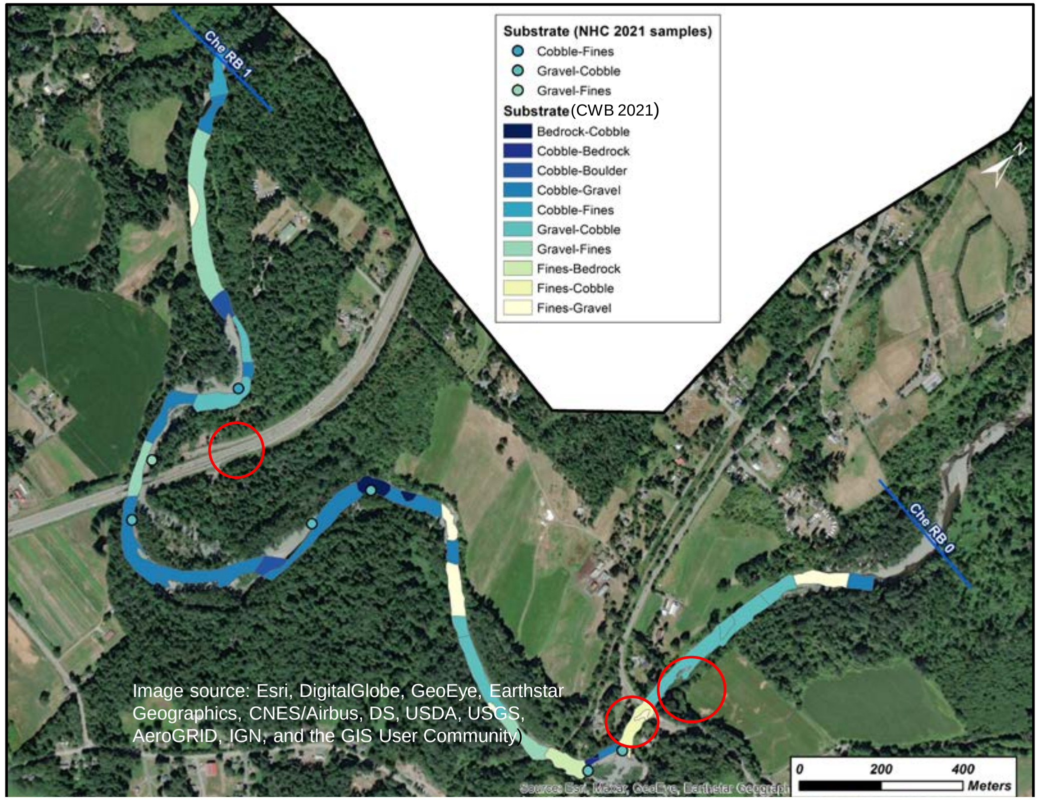
Image source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus, DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community)

Channel Assessment Meso-habitat Spatial Data (Cowichan Watershed Board 2021)

Stream Substrate

A detailed classification of stream substrate is presented in the left panel below. The data is derived from low-flow Wolman pebble counts collected during the summer of 2021 (Cowichan Water Board, 2021).

- The river-bed is dominated by cobble to gravel sized sediment with localized bedrock outcrops and deposition of fines.
- Upstream of the three bridges – Highway 1, the railroad bridge, Highway 1a bridge (circled in red) – the stream substrate is locally finer than upstream and downstream locations. This localized fining of sediment caliber is likely produced by backwatering effects during high flows. The bridges impose an artificial constraint on channel width, which reduces the amount of flow that can be conveyed at a given time. This causes the flow of water to slow down and leads to upstream sediment deposition.
- NHC pebble counts (2021) were collected at a relatively higher flow than the CWB (2021) data, which reduced the sample area coverage.

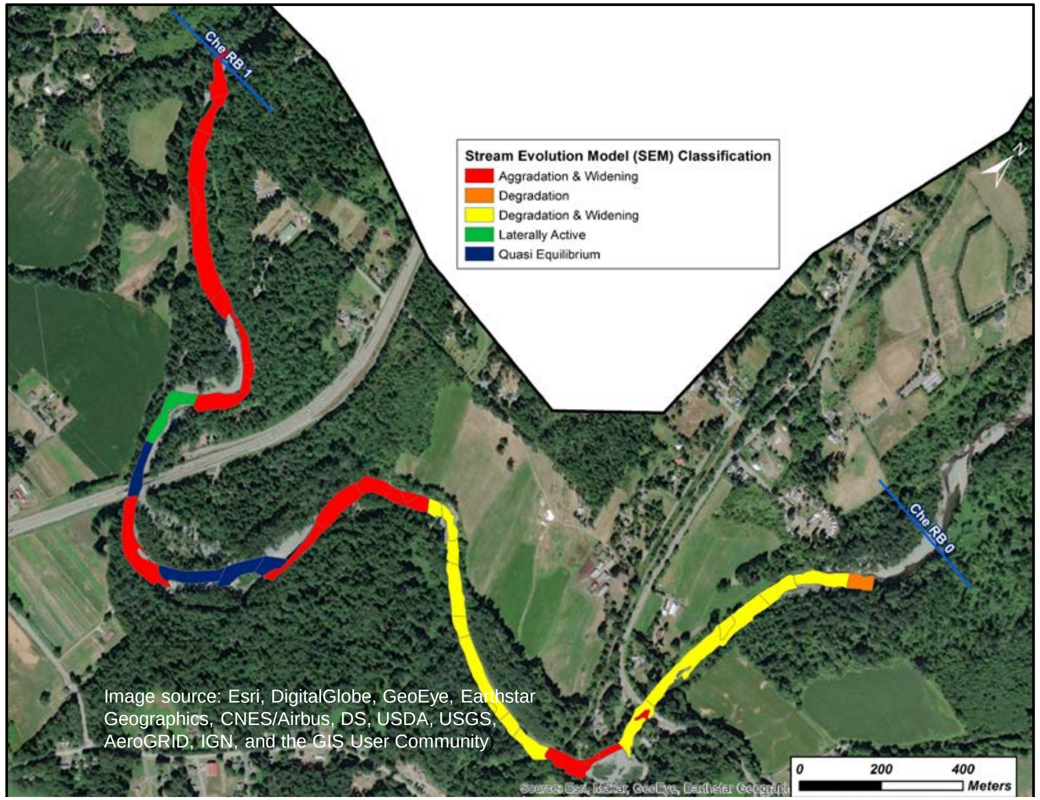


▲ Stream substrate classification. Red circles highlight localized sediment fining upstream of bridges.

Stream Evolution Model

The geomorphic condition of the channel, as expressed by the Stream Evolution Model (SEM) classification (Cluer and Thorn, 2004) is presented in the right panel below. Data provided by the Cowichan Water Board (2021).

- Upstream of Highway 1, most of the channel is in a state of aggradation and widening. The channel is laterally active locally downstream of a vegetated island, whereby a back-channel rejoins the mainstem.
- The lower half of the reach is defined to be mostly in a state of degradation and widening. Between the railroad bridge and Highway 1a bridge, the channel is in a state of aggradation and widening (described on Page 31).
- These results agree with NHC's measurements of vertical bed elevation changes from 1986 to 2021 (Page 31).



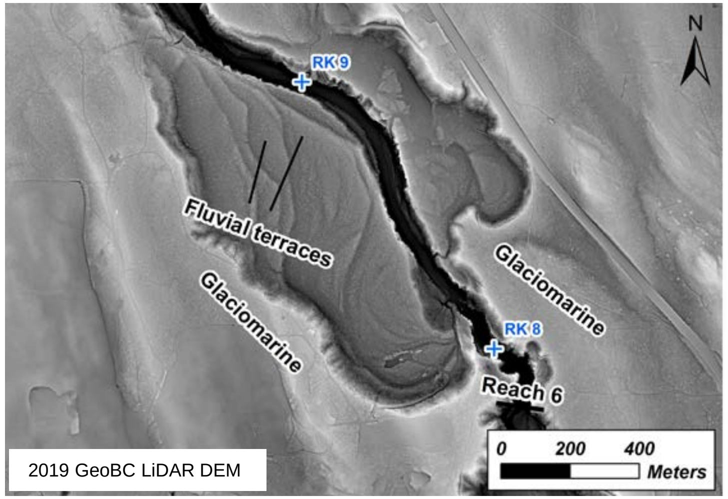
▲ Stream Evolution Model (SEM) classification of the channel's geomorphic condition.

7 REACH-SCALE CHANNEL CHARACTERISTICS AND DOMINANT PROCESSES

Reach 7 (RK 9 to RK 7.8) : Confined Channel Reach

- Through Reach 7, the Chemainus River flows southeast within a roughly 40 m wide channel with a steeper gradient (0.0064 m m^{-1}) than downstream reaches.
- Near the downstream extent of Reach 7 (around RK 8) the channel is confined on either side by valley walls approximately 40 m high, composed of resistant glaciomarine sediment.
- Upstream of RK 8, the channel is bordered on either side by terraces that sit 20 m to 25 m above river level. During a period of sea-level lowering, the stream likely cut these terraces in older deposits (Halstead, 1966). The modern-day channel appears to be underfit and no longer erodes the terrace surfaces.
- Channel banks are well-vegetated, contributing to high bank stability in Reach 7.
- Reach 7 is just upstream of the hydraulic model extent, so information on shear stress and flood levels was not available for this study.

The lack of major in-channel storage sites through this reach is indicative of a transport-dominated regime. Sediment and large woody debris (LWD) are typically conveyed farther downstream with only transient gravel bars forming and deforming year to year within this reach.

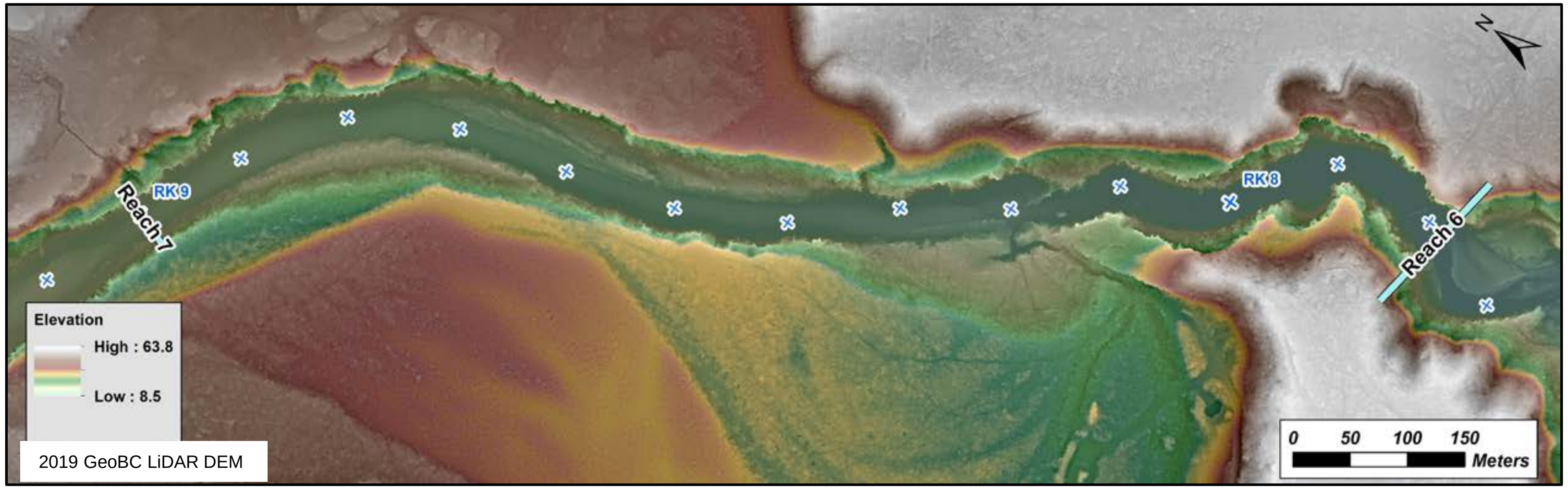


2019 GeoBC LiDAR DEM

Reach 7	
Reach Length (m)	1,217
Average Slope (m m^{-1})	0.0064
D_{50} (mm)	-
Mean Erosion Rate (m yr^{-1})	-

Note: D_{50} refers to the median sediment grain size diameter, measured from bar surface photos.

2021 FLNRORD orthophoto



2019 GeoBC LiDAR DEM

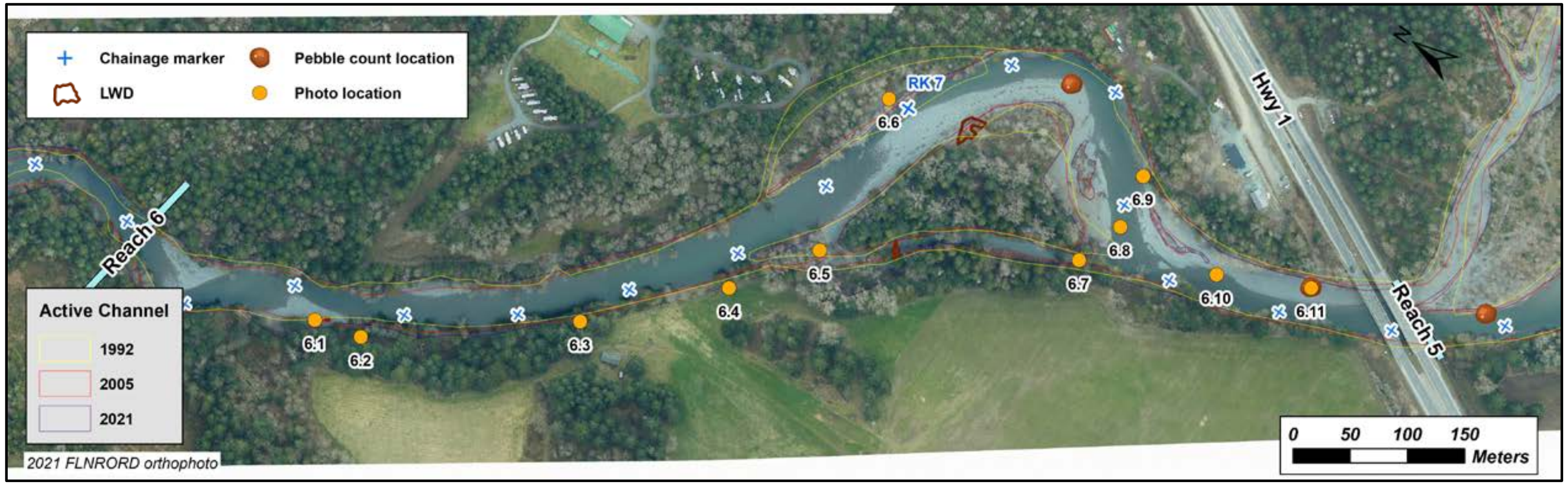
Note: RK refers to the River Kilometer distance measured along the channel thalweg, upstream of the approximate seaward extents of the estuary (northeast of the northern Willy Island passage). Each 100 m channel distance is marked with an 'X' and every RK is labelled.

Reach 6 (RK 7.8 to RK 6.4): Reach Morphology

- In Reach 6 the river exits a confined canyon and flows onto a broad alluvial plain.
- At the upstream end of the reach, the channel flows through a straight channel, roughly 40 m wide. Small lateral bars at the top of the reach consist of boulders and cobbles, often with LWD accumulations, indicative of a high-energy environment.
- In the upstream end of the reach bedrock outcrops and tall terraced banks constrain the channel position to the north. Along the southern channel boundary, a discontinuous earthen berm runs parallel to the river, which reduces overbank flow onto the floodplain during flooding.

▼ Photo 6.1 Boulders and coarse cobble on the bar surface.

▼ Photo 6.2 Bedrock outcrop along the left (north) bank of the channel.



▲ Photo 6.3 Earthen berm reduces the amount of flow that spills out onto the floodplain during peak flood events.

Reach 6	
Reach Length (m)	1,415
Average Slope (m m^{-1})	0.0014
D_{50} (mm)	51
Mean Erosion Rate (m yr^{-1})	0.4

- Near RK 7, the Chemainus river splits into two channels around a vegetated island and bar complex. The island formed prior to 1950, and appears stable over time, increasing in extent as vegetation establishes and matures.
- Near RK7, the main channel is bounded to the north by terrace bluffs. Opposite the bluffs, sediment has accumulated along the margin of the island, ranging from coarse cobbles near the head, to finer gravels at the tail.
- A secondary channel, 10 km to 15 m wide, flows south of the island. This channel is shorter and straighter than the main channel, and potentially offers a more energy-efficient path to convey flow. A review of historical air photos suggests that the channel has become increasingly active over time.

Note: Left and right channel descriptors refer to a downstream facing view of the channel.

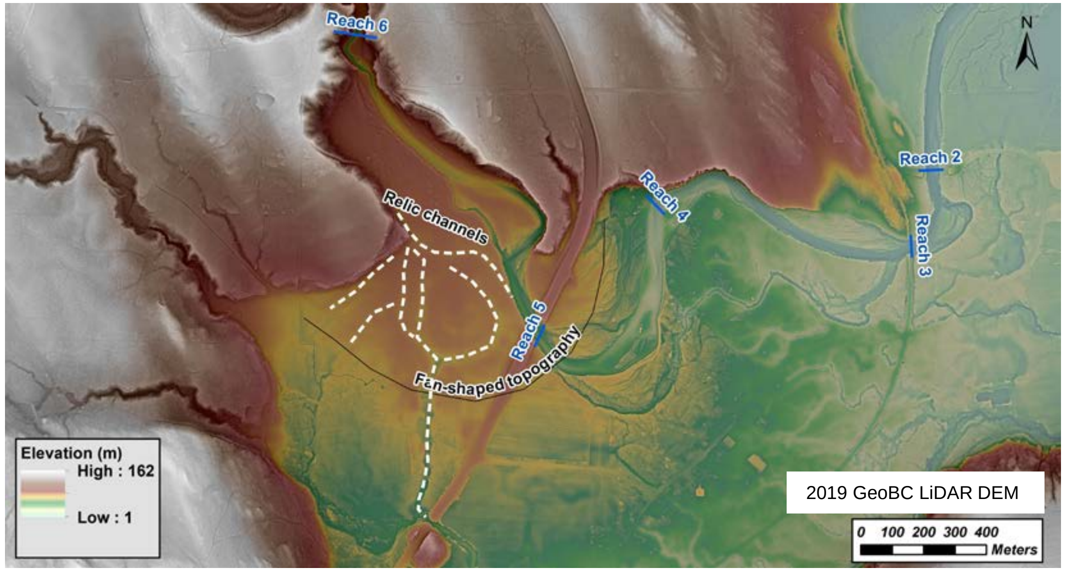
▶ Photo 6.4 Overbank sand deposits 0.1 to 0.2 m deep.

Reach 6 (RK 7.8 to RK 6.4): Partially Confined Channel Reach

As the river exits confinement from the steep terraced banks it becomes increasingly more coupled with the adjacent floodplain area. During large floods, overbank flow spills out onto the floodplain depositing fine sediment carried in suspension and over time produces the fan-shaped depositional pattern observed in the DEM.

Relic channels in the floodplain south of the modern-day channel, reveal insights into historical channel positions. Should the earthen berm that runs along the southern channel bank fail or be removed, these old channels are potential primary pathways for overbank flow.

Analysis of a simulated 200-yr flood event shows that at this stage, roughly 70% of the discharge is conveyed within the Reach 6 channel banks, and 30% of the discharge flows south, overbank across the floodplain. Log jams or sediment accumulations could alter the channel conveyance capacity over time.

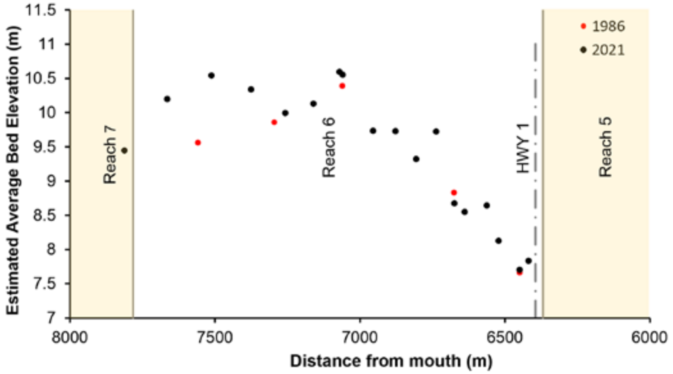


▲ DEM illustrating the fan-shaped topography across the Chemainus River floodplain.

▶ Photo 6.5 LWD accumulation and sediment lobes on the island.

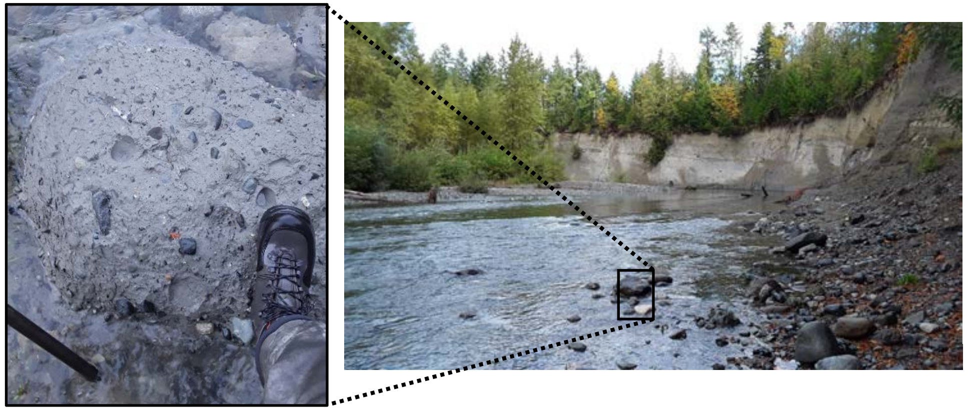
▼ Photo 6.6 A steep riffle at the head of the bar. Surface sediment at the bar head is primarily cobbles.

▼ Plot of average bed elevation in 1986 and 2021 in Reach 6 indicating apparent channel aggradation (see Page 31 for more details).



▼ Photo 6.7 (Upstream view) Back-channel has multiple downed trees spanning the channel width.

▶ Photo 6.8 Fine to medium gravels on the tail of the bar opposite the bluff. This is much finer sediment than found along the toe of the bluff and head of the next bar downstream highlighting the within-channel spatial variation in shear stress and stream energy.



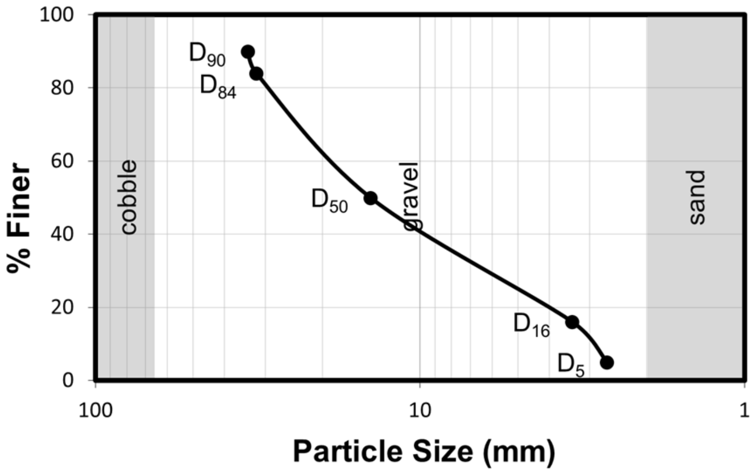
◀ Photo 6.9 Glaciomarine deposits composed of silt, clay, stony clay, and till-like mixtures up to 20 m thick provide resistant banks to the channel through this reach. This feature has kept the position of the contemporary channel position relatively stable since deglaciation (Halstead, 1966).

Reach 6 (RK 7.8 to RK 6.4): Upstream of Highway 1

The November 2021 flood caused erosion at the toe of the right (southern) bank, which is composed of compact sands and gravels. While this area has historically been relatively laterally stable with little to no bank retreat observed since 1950, the right bank is directly exposed to flow forces where the mainstem channel and back channel rejoin at the downstream end of the island.

An increase in the proportion of flow directed into the southern channel would have direct implications for the dynamics of downstream-reaches. Specifically, it may change the direction in which flow attacks channel banks in Reach 5.

- Downstream of the vegetated island, the two channels rejoin into a single mainstem. Here, sediment has accumulated along the left side of the channel, while the channel thalweg flows close to the right (south) bank.
- The artificial constraint on channel width imposed by the Highway 1 bridge creates upstream backwatering during high flows and creates a localized fining of surface sediment caliber along the left bank deposit. The median size of sediment upstream of the bridge is in the range of 15 mm to 30 mm, while further downstream pebble counts indicate a median size of surface sediment in the range of 40 mm to 50 mm.

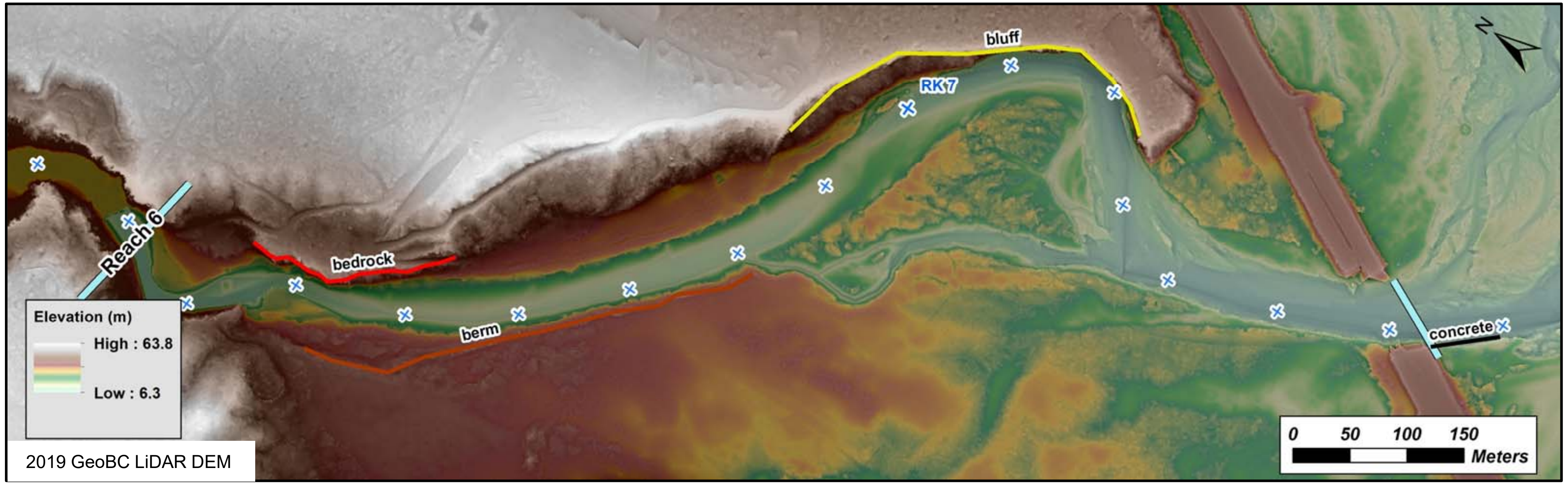


▲ Pebble count taken at RK 6.45, just upstream of the Highway 1 bridge. D_{90} refers to the sediment grain size diameter that is not exceeded 90% of the time in the sample dataset.

◄ Photo 6.11 Gravel-sand mix on the bar tail upstream of the Highway 1 bridge.

▲ Photo 6.10 At the mid-channel bar the substrate is much coarser than that seen on the tail.

▲ Photo 6.7 (Downstream view). Toe erosion along the right (southern) bank. This bank line has been relatively stable historically.



Reach 5 (RK 6.4 to RK 5.5): Reach Morphology

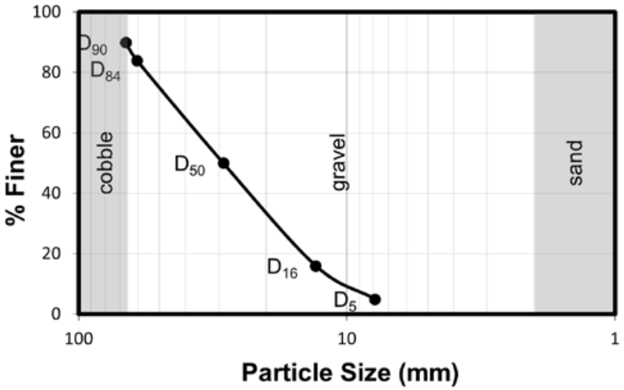
Reach 5 of the Chemainus River falls partially within the boundary of the Halalt First Nation administrative boundary. Reach 5 is a primary depositional zone and is laterally unstable.

- The confinement imposed by the Highway 1 bridge plays a large role in the stability and morphology of Reach 5.
- Downstream of the bridge, the river enters a zone of hydraulic expansion and is a prominent depositional zone. At higher flows, water and sediment is conveyed through multiple channels around islands and over bar tops, re-working existing sediment deposits.
- LWD jams on islands have been modified and anchored using heavy cable and ballast. These anchored jams help control local channel hydraulics and habitat conditions by altering the spatial patterns of scour and deposition (Abbe and Montgomery, 1996).
- At present, the ability for the river to laterally migrate across the valley bottom is limited in places by rock armouring along the right (southern) bank. There is evidence in the DEM of past channels flowing through the floodplain south of the modern-day channel.

Photo credit: CVRD

◀ Chemainus River downstream of the Highway 1 bridge. Photo shows high-flow channel on the inside of the bar, and log jams on the vegetated island.

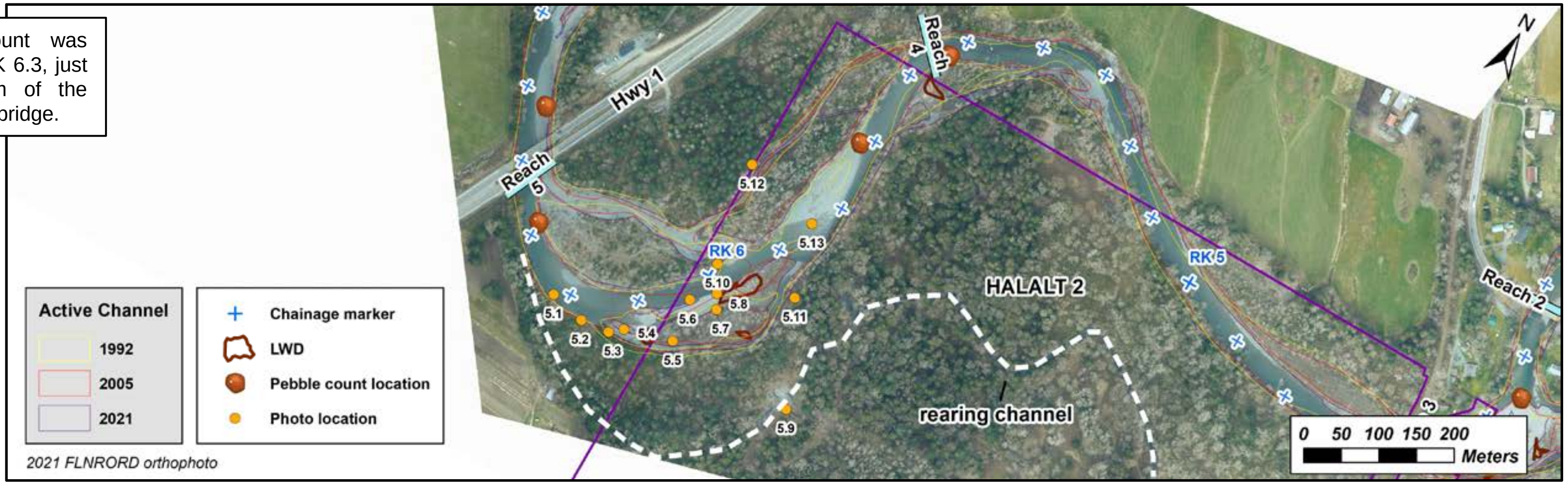
▼ Photo 5.8 Upstream log jam on the vegetated island.



◀ Pebble count was taken at RK 6.3, just downstream of the Highway 1 bridge.

Reach 5	
Reach Length (m)	813
Average Slope (m m^{-1})	0.0029
D_{50} (mm)	38
Mean Erosion Rate* (m yr^{-1})	0.9

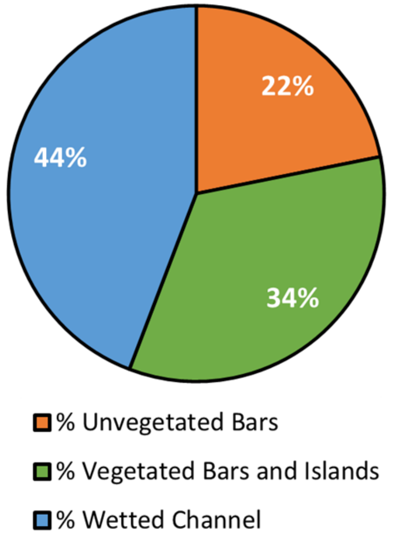
* Mean erosion rate calculated from changes in bankline position from 1950 to 2021 but does not include the substantial erosion produced in the November 2021 flood event. This is discussed in more detail on Page 19.



Reach 5 (RK 6.4 to RK 5.5): Point Bar

Since 1975, vegetation has established and matured on the bar downstream of Highway 1 providing increased flow resistance locally. The distribution of vegetated surfaces (on islands and vegetated bars) appears to be an important control on the morphodynamics of Reach 5.

- Peak flood events overtop and carve channels into the bar surface, producing variations in sediment caliber across the bar. Sand and fine gravel is transported along back channels and high-elevation surfaces, while areas closer to the main low-flow channel exhibit a coarser texture.
- A municipal water well is located on the interior of the bar and has been reinforced with heavy rock armour to provide protection from scour. The area is in the vicinity of a high-flow channel and is potentially exposed to erosion from annual flood events.
- In 2021, sediment was removed from the bar tail adjacent to the wetted channel to allow flow through the area and to lessen the force of flow against the bank opposite of the bar (DR Clough, 2007).

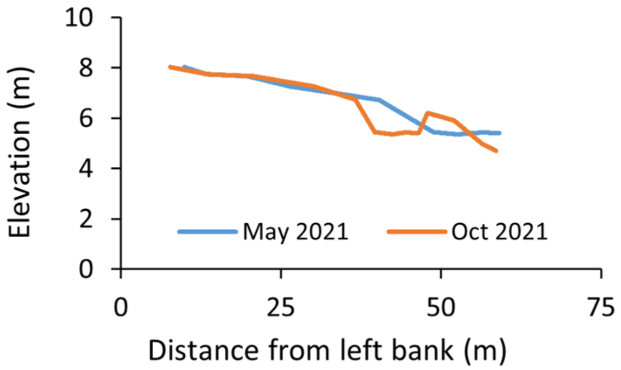


▲ Proportion of unvegetated bars, vegetated bars and islands, and wetted channel in Reach 5 in 2021.

▲ Photo 5.10 High-flow channel on the bar surface. Sandy lobes are left behind during the falling limb of the flood as water levels drop and the finer sediment falls out of suspension. The boulders at the right of the photo armour the water well installed on the bar.

▼ Photo 5.12 Fine to medium gravel and sand is transported through a back-channel along the inside of the point bar. The channel is about 2.5 m wide and incised approximately 0.3 m into the floodplain.

► Bed lowering along the left side of the channel at RK 5.8, resulting from sediment removal in 2021.



► Photo 5.13 Sediment was removed from the bar tail (2021) to create a wider wetted channel and to reduce flow towards the opposite bank.

Reach 5 (RK 6.4 to RK 5.5): Bank Erosion

Opposite the point bar, the right (southern) channel bank is on the outside of a meander bend and is susceptible to erosion from upstream flows. This section of bank line is highly significant because of its proximity to the Halalt First Nation band office and community facilities, and because roads and houses in the vicinity would be threatened should the banks erode in this direction.

- Approximately the first 40 m of right bank downstream of the Highway 1 bridge is reinforced with concrete blocks and has shown little to no erosion since 1950. Field visits (in 2021) indicate some of the concrete blocks are absent along the toe but are visible higher up on the bank.
- Downstream of the concrete, the channel bank is composed of loosely consolidated layers of cobble, gravel and sand with varying degrees of root-strength provided by riparian vegetation. Coarse gravel and cobble deposits in the bank stratigraphy are deposited by relatively high energy flood events, whilst finer-grained sand deposits reflect deposition during more moderate flow conditions.
- Mapping of historical bank line positions shows that from 1950 to 2021, the outer bank has retreated at an average rate of 0.9 m per year with year-to-year variations based on the flow regime.
- In November 2021, the atmospheric river that hit the Pacific Northwest produced a substantial flood on the Chemainus River. Topographic survey measurements collected pre- and post-flood indicate that this event caused the outer bank to retreat by 2.5 to 6.3 m. This magnitude of bank retreat is 2.7 to 7 times higher than the historical erosion rate.
- The largest magnitude of bank retreat in Reach 5 (in 2021) was observed in the downstream most section of bank line, just upstream of the island. This area is most directly exposed to high-velocity flows from upstream and has a very shallow root network offering little to no stabilization.

▲ The November 2021 flood eroded a 200 m section of bank line downstream of Highway 1. As a result, the bank retreated away from the channel by up to seven metres. 2021 FLNRORD orthophoto.

▲ Photo 5.1 Exposed roots offer relatively more resistance to erosion than farther downstream. However, the silty bank material is relatively more erodible than the composition downstream.

▲ Photo 5.2 Exposure at the downstream end of the eroding bank line. The sandy layer near the toe is easily eroded. Coarser material is loose and uncompacted. The roots through upper horizon offer minimal stabilizing benefit.

Reach 5 (RK 6.4 to RK 5.5): Avulsion Potential

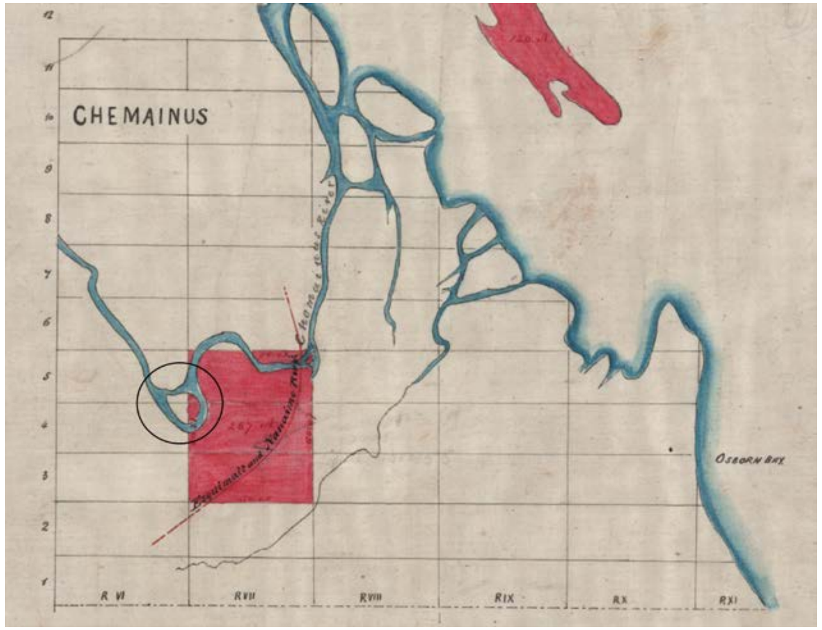
A historical side channel, approximately 6 m to 8 m wide, has been deepened and is used by the Halalt Fisheries for juvenile fish rearing (Chief Thomas, pers. comm. 3 August 2022). A relic channel located on the right (south) bank of the Chemainus River connects to the Halalt Fisheries channel, and if a triggering mechanism produces a breach of the channel banks near the relic channel, it will provide a preferential pathway to convey overbank flow downstream along a similar hydraulic gradient to the contemporary main channel.

This location is prone to channel avulsion.

- The risk of avulsion into the relic channel would be exacerbated by LWD accumulations or sediment aggradation near the entrance to the channel.
- A map produced in 1877 suggests that historically flow was conveyed across two channels through Reach 5, where the southern channel appears to overlap the position of the Halalt Fisheries rearing channel. This provides supporting evidence for the possibility of an avulsion in this reach to return to a similar multi-channel configuration as occurred in the past.

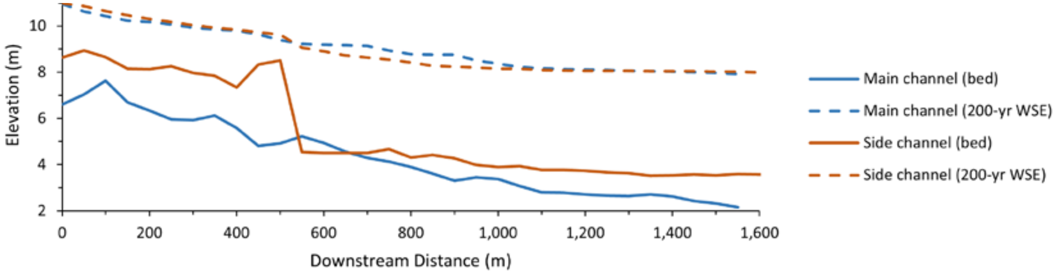
▲ Photo 5.9 The floodplain channel and pond system is used for rearing juvenile fish by Halalt Fisheries. Photo at left shows a floodplain channel in August 2021. Photo at right shows the facility following the November 2021 flood event.

▼ Map of the Chemainus River from 1877 (Indian Affairs Survey Records No. BC 220) shows Reach 5 historically was split into multiple channels. Shaded red areas represent Halalt First Nation administrative boundary.

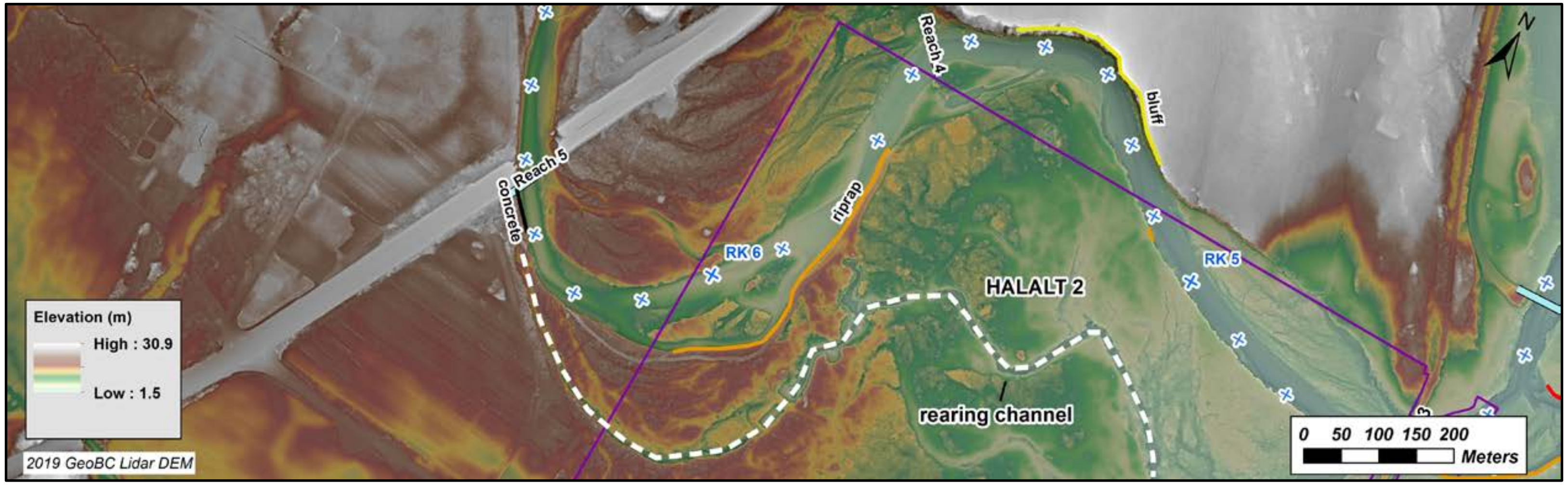


▶ Comparison of channel bed and water surface profiles in the mainstem and relic side channel.

Main channel	
Length (m)	1,620
Average Gradient (m m^{-1})	0.0029
Side channel	
Length (m)	1,736
Average Gradient (m m^{-1})	0.0031



▼ DEM showing a visible relic channel path.



7 REACH-SCALE CHANNEL CHARACTERISTICS AND DOMINANT PROCESSES

Reach 5 (RK 6.4 to RK 5.5): Island and Side Channel Erosion

Given the angle of exposure from upstream flows, and the deposition of sediment on the opposite side of the channel, the southern channel bank and island is threatened by erosion during future flood events.

- Near the right (south) bank of Reach 5, an approximately 10 m wide side-channel flows around an elongate vegetated island. The island and secondary channel bank lines are exposed to high-velocity flows, and as such have been the focus of ongoing river management works.
- Upstream of the island, the southern channel bank is armoured with riprap and is connected to the head of the island via placed LWD and boulders.
- The secondary channel flowing behind the island is also reinforced with riprap along its outer bank. In spot areas where riprap is absent, the banks are composed of uncompacted sand and gravel at the upstream end and soft fine-grained loamy material downstream where the back-channel rejoins the mainstem.
- The island bank adjacent to the main channel experiences high-velocity flows during peak floods and has been reinforced with piled gravel and placed LWD.

▲ Photo 5.5 Riprap along the right channel bank behind the island.

▲ Photo 5.4 Wattle fencing at the head of the island installed in 2021.

▲ Photo 5.11 Soft, loamy material along the bank is easily eroded.

▲ Photo 5.7 Gravel pile-up along island bank is reinforced with LWD.

▲ Photo 5.6 Coarse cobble and boulder substrate on the vegetated island is indicative of a high energy environment. The river mobilizes smaller particles downstream.

▼ Photo 5.3 LWD was placed at the entrance to the side channel to reduce flow into this area. The LWD connects riprap armour along the upstream bank to the log jam at the head of the island.

Reach 4 (RK 5.5 to RK 4.6): Channel Confinement

Reach 4 of the Chemainus River resides partially within the Halalt First Nation administrative boundary.

From RK 5.5 to RK 4.6, the river flows within a 30 m to 40 m wide bedrock channel with little sediment covering the bed. The lack of sediment cover means that the channel slope through this reach is primarily controlled by the bedrock over which it flows.

- The channel is confined to the north by terrace bluffs that extend 15 m to 20 m above the river bottom elevation. These bluffs are composed of compact fine-grained sediment of marine/glaciomarine origin, the same unit described in Reach 6.
- The bluffs are more resistant to erosion than other alluvial banks within the channel and have remained relatively stable in the air photo record dating back to 1950. However, undercutting of the toe of the bluff was observed during the November 2021 atmospheric river flood. Given the height of the bluffs, continued undercutting by fluvial erosion has the potential to trigger a mass wasting event which could block the river. For this reason, these banks were flagged as geotechnical hazards in the geomorphic hazard maps.
- Opposite the bluffs, sediment has accumulated on the inside of a channel bend forming a point bar. This site has historically been a sediment sink and has been the focus of past sediment excavation efforts.

◄ Photo taken at low-flow, exposing the bedrock channel bed at the top of reach 4. This provides an important control on the channel gradient in this reach.

▲ Photo 4.1 from August 2021 prior to the winter storm season.

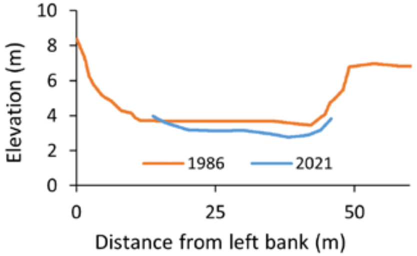
▲ Photo 4.1 Erosion at the toe of the bluff from the November 2021 flood.

Reach 4	
Reach Length (m)	937
Average Slope (m m^{-1})	0.0022
D_{50} (mm)	34
Mean Erosion Rate (m yr^{-1})	0.7

Reach 4 (RK 5.5 to RK 4.6): Upstream of the Railroad Bridge

Downstream of the point bar, Reach 4 has few sediment storage sites, and is characterized by a transport-dominated regime. Sediment appears to be flushed through this reach and accumulates downstream of the railroad bridge in Reach 3.

- The right (south) bank of the channel shows signs of undercutting and has been reinforced locally with log spurs and riprap. Despite this, the historical mean rate of erosion (0.7 m yr^{-1}) through Reach 4 is low compared to other mapped reaches.
- Between RK 5.5 and RK 5.1, where the channel is confined to the north by the bluffs, there has been limited lateral migration over the air photo period of record. However, repeat surveys at approx. RK 5.1 indicate that scour (-0.30 m vertical change) occurred between 1986 and 2021.



◀ Plot showing scour at RM 5.1 between 1986 and 2021 based on repeat surveys.

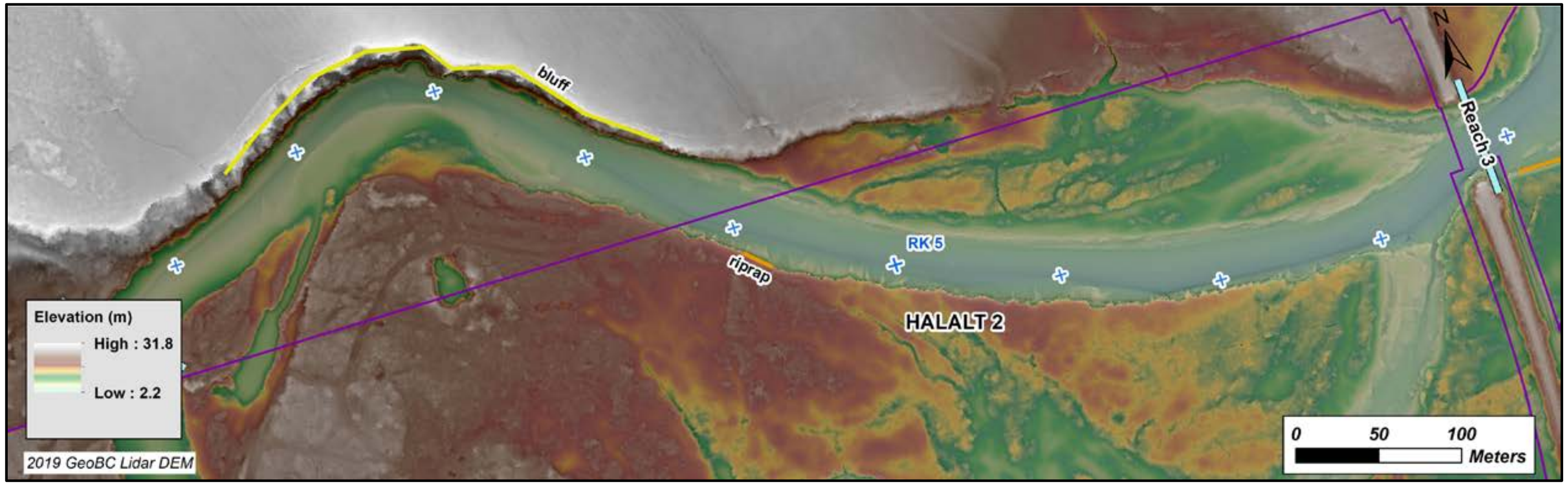
- Upstream of the railroad bridge, mature vegetation has increasingly established on an old gravel bar on the left (north) side of the channel since 1950. This has produced a straighter channel planform over time.
- Backwatering produced by the channel constriction at the railroad bridge likely contributes toward the localized deposition of fine sediment along the left margin of the channel.

▶ Photo 4.3 Log spurs along the right bank of the channel designed to deflect flow and mitigate against erosion. Rocks placed along bank to supplement the armouring.

▶ Photo 4.4 The Halalt Fisheries rearing channel rejoins the Chemainus River just upstream of the railroad bridge.

▲ Photo taken from the railroad bridge during low-flow conditions, looking upstream at the exposed sand and gravel bar and vegetated area on the inside of the bar.

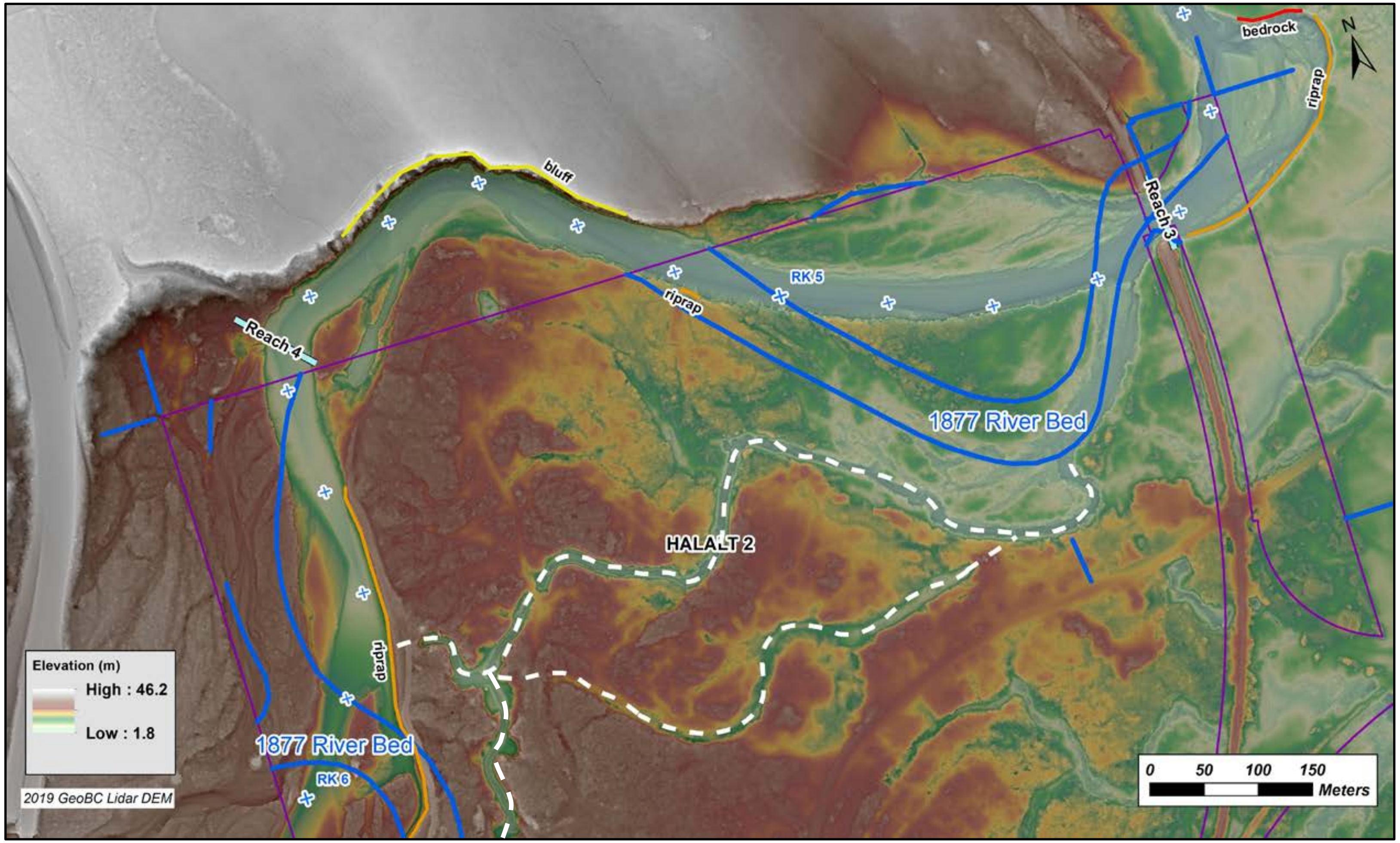
▼ Photo 4.2 Undercutting and exposed root structure along the right bank of the channel.



Reach 4 (RK 5.5 to RK 4.6): Relic Channel

There is a risk of avulsion into the relic channel if a triggering mechanism produces a breach of the channel banks near the upstream entrance to this historic channel in Reach 5.

- A Canada Lands 1877 survey of the area indicates the presence of an approx. 55 m wide old river-bed south of the present-day channel from approximately RK 5.1 to RK4.7.
- This southern relic channel comprises part of the historic channel migration zone and occurs within the Halalt First Nation lands.
- If the log spurs and riprap at RK 5.1 (described on Page 23) do not control the local undercutting along the right bank, and if further erosion occurs at RK 5.1 to RK 5.2, it is possible that the Chemainus River may re-occupy the relic channel at RK 5.1 to RK 4.7.
- South of the approx. 55 m wide old river-bed is another, narrower (approximately 15 m wide) relic channel that runs south of the present-day Chemainus River channel from approximately RK 5.9 to RK 4.8 (shown with the white dashed line on the figure at right).



▲ DEM showing historical channel and visible relict channel paths.

▲ Historical map of the Chemainus River from the 1800's (Map of Chemainus District. Undated; traced by R. Cridge at the Land Title Office Victoria. Scale 4 Inches = 1 Mile or 20 Chains = 7 Inches, Surveyor General's Vault, Land Title and Survey Authority of British Columbia. 35 Tray 1 Vancouver Island) overlaid by the Canada Lands 1877 river-bed survey (blue outline) and the 2021 Chemainus River location (yellow transparent shading).

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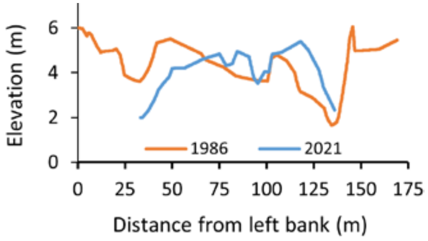
Reach 3 (RK 4.6 to RK 4.3): Depositional Zone

The railroad and Highway 1A bridges form a distinctive hydraulic control on the system and form a zone of sediment and LWD deposition in between them.

- A 10,000 m^2 partially-vegetated gravel bar occupies 80% to 90% of the active channel width in the middle of Reach 4. In 1975, this bar was attached to the left (east) bank but has since been re-worked and re-shaped such that the 2021 bar is closer to the right bank and the primary low-flow channel is located west of the bar.
- Stands of vegetation on the bar surface tend to trap logs floating downstream, often forming jams. Between the patches of vegetation, high-flow channels have been carved across the bar top.
- The outer (east) bank of Reach 4 is armoured with riprap, which has maintained the position of this bank line since 1992. Downstream of the riprap, a bedrock outcrop is exposed along the channel bank, also maintaining the position of the bank line historically. The hardened bank line exerts a primary control on reach-scale hydraulics and patterns of scour and fill.



◄ Surveyed bed elevations at the mid-channel bar at RK 4.5. Between 1986 and 2021, the left channel deepened and widened. Accretion occurred along the right margin of the mid-channel bar and within the right channel.

▼ Coarse to very coarse gravel deposits along the bar edge.

▲ The bedrock outcrop along the right channel bank provides increased resistance to erosion, acting as an important control on channel stability and patterns of scour and deposition in this reach.

◄ 3.1 Small log jam spanning the back channel flowing behind the gravel bar.

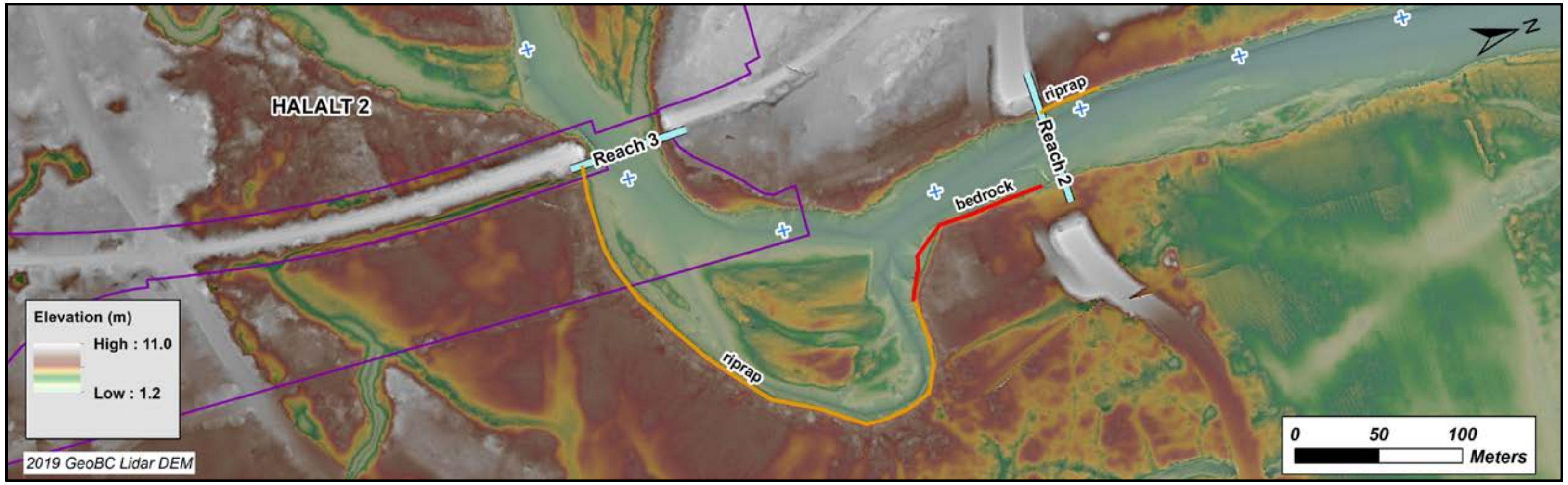
◄ Photo 3.2 Back-channel bank is armoured by riprap, which shows signs of scour along the toe.

Reach 3 (RK 4.6 to RK 4.3): LWD Accumulation

▲ Massive pile up of LWD at the Highway 1A bridge from January 2022.

Reach 3	
Reach Length (m)	296
Average Slope (m m^{-1})	0.0018
D_{50} (mm)	33
Mean Erosion Rate (m yr^{-1})	0.7

▲ Photo 3.3 Multiple logs, floated downstream by a 2021 flood, caught on the foundation structures of the Highway 1A bridge.



Reach 2 (RK 4.3 to RK 3.3): Downstream of Highway 1A

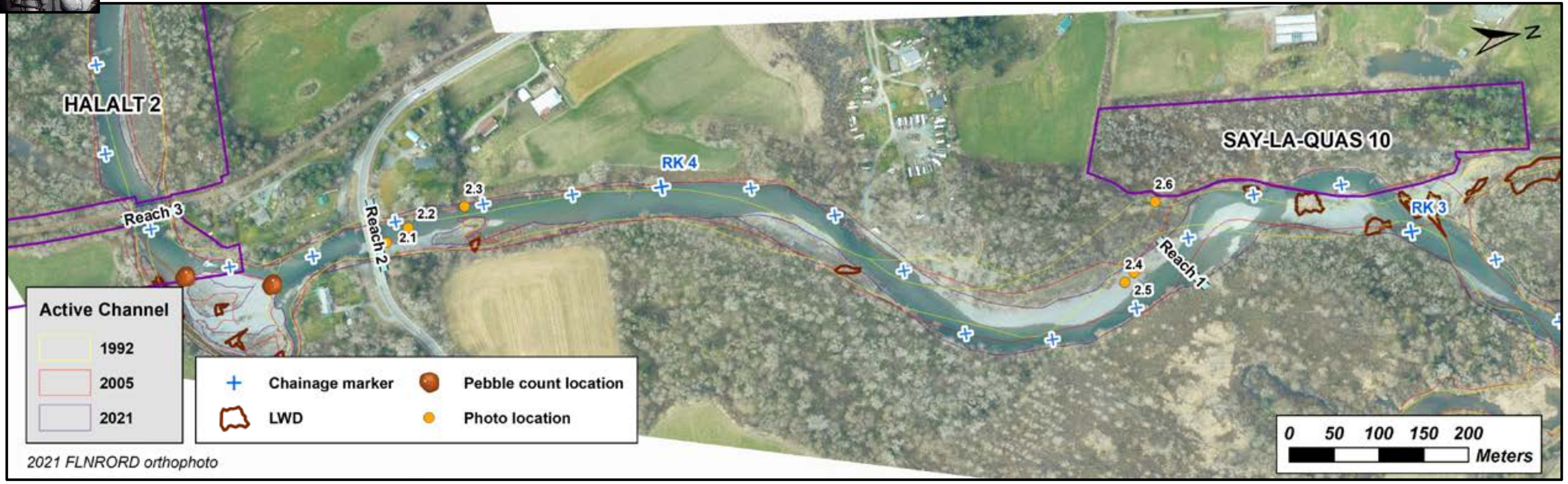
Downstream of the Highway 1A bridge, the river flows north along a 40 m to 50 m wide channel with gravels deposits along the right channel margin.

- Deposition in this area is largely influenced by hydraulic expansion effects downstream of the bridge, and localized dynamics associated with LWD trapping patterns on the upstream side of the bridge.
- Bedrock along the right (east) bank at the downstream end of Reach 3 provides increased flow resistance locally and may help deflect some portion of the flow towards the left (west) side of the channel.
- Riprap armouring has been installed along an approximately 40 m section of the right bank line downstream of the bridge. The channel has widened in this area since 1992, likely prior to riprap installation.

▶ Photo 2.3 Downstream of the riprap, the bank is composed of silty material with clay and fine sand. The toe of the bank is a gravel-sand mix.

▼ Photo 2.2 Riprap along the left bank of the channel prevents scour.

▲ Photo 2.1 Sediment accumulation along the right side of the channel downstream of the Highway 1A bridge.



Reach 2	
Reach Length (m)	996
Average Slope (m m^{-1})	0.0015
D_{50} (mm)	-
Mean Erosion Rate (m yr^{-1})	0.8

Reach 2 (RK 4.3 to RK 3.3): Gravel bar

At RK 3.5, a gravel bar attached to the left (west) channel bank borders the Stz'uminus First Nation's Say-La-Quas 10 administrative boundary to the north. Remnants of a historical village site were identified by Stz'uminus First Nation Band Council member and cultural consultant Arthur Jim (18 February 2022).

- Bar texture is finer than observed in upstream reaches, with gravel deposits along the bar head and bar margin, and a high proportion of sand deposited on the mid-bar and bar tail.
- During high-flows, water is conveyed across bar-top channels and a back-channel that flows behind the bar.
- As the bar has developed and migrated downstream since 1992, the outer bank across from the bar has been eroded to accommodate the space occupied by new bar area.
- Across from the bar, riprap armouring limits the channel's ability to erode an approximately 100 m long section of its banks. The erosive force focused on this area is likely transferred downstream, affecting patterns of downstream erosion.

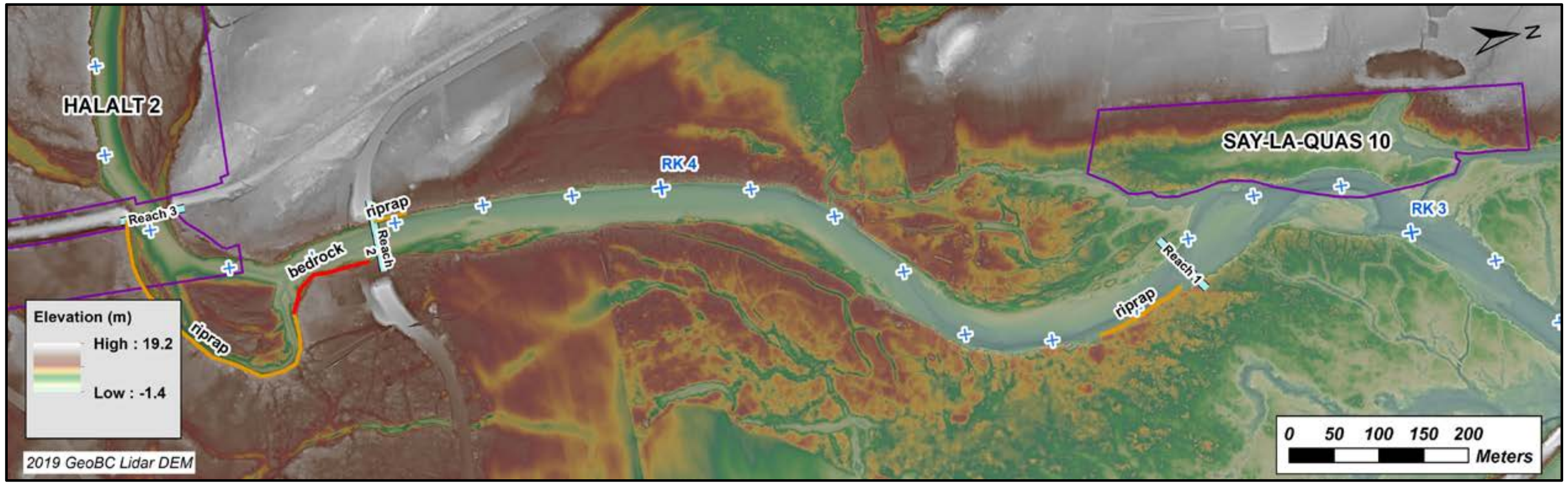
▲ Photo 2.5 The bar tail has a high proportion of sand. The bank opposite the bar has been stabilized with riprap.

▲ Photo 2.6 Channel flowing behind the bar-island complex.

▲ Photo 2.4 LWD deposited across the tail of the bar.

Comparison of cross sections surveyed in 1986 and 2021 show slight degradation in the middle and downstream portions of Reach 2, with unit vertical change of -0.3 m at RK 3.7 and RK 3.9. Slight aggradation (unit vertical change of 0.1 m) was observed at RK 4.3, just downstream of the Highway 1A bridge.

▲ A channel avulsion occurred between 1950 and 1968.Since then, the gravel bar has become increasingly stable as vegetation has established on the bar interior. The bar and meander bend have migrated downstream since 1992 as sediment is eroded from the bar head area and deposition occurs on the bar tail.



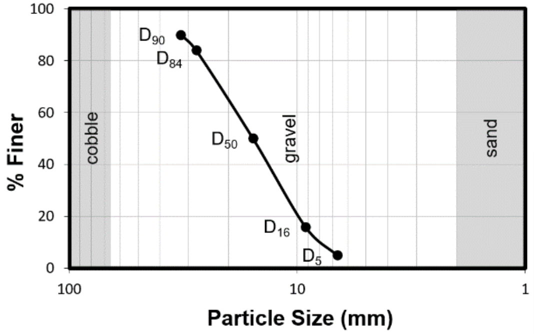
7 REACH-SCALE CHANNEL CHARACTERISTICS AND DOMINANT PROCESSES

Reach 1 (RK 3.3 to RK 0): Distributary Channel Network

The distributary channel network shifts and evolves through time based on complex interactions between fluvial and coastal processes. Specific channels may become activated or abandoned based on rates of sediment aggradation, LWD jams, and re-working of sediment by tidal currents and wave action.

The upstream end of Reach 1 is bordered to the west by the boundary of the Say-La-Quas 10 administrative boundary. The lower Chemainus River distributary channel network located near RK 3 was identified as sacred and a former fishing, harvesting, trapping, hunting and village site for the Stz'uminus First Nation peoples (Arthur Jim, pers. comm. 18 March 2022).

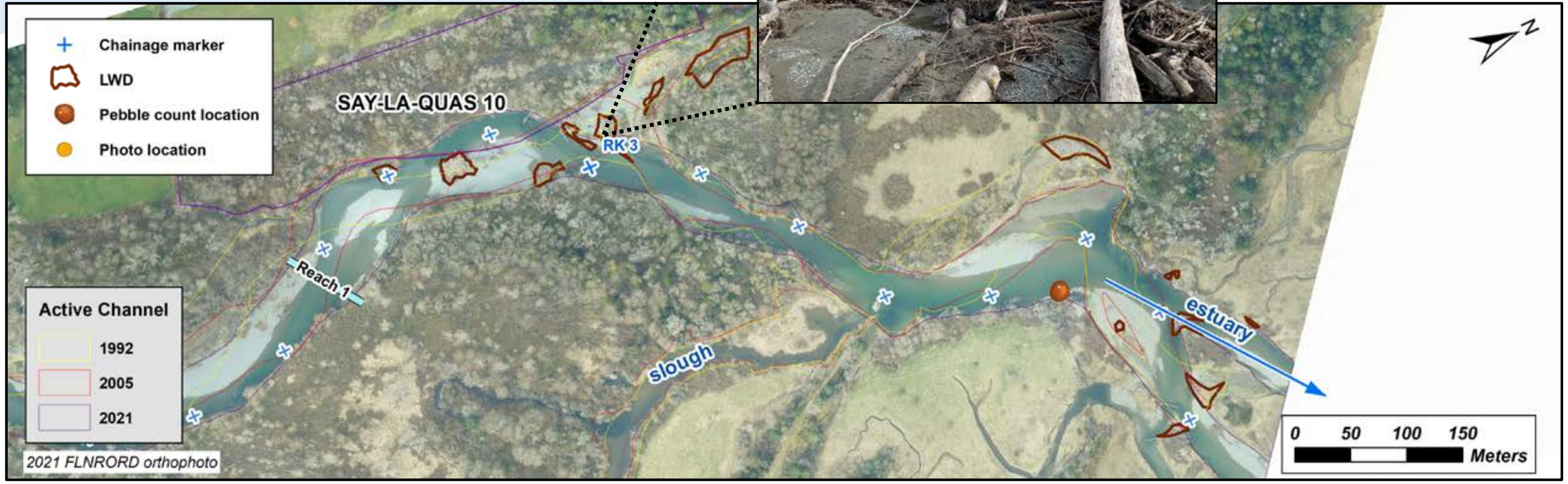
- The primary flow path for the Chemainus River used to flow farther north and has been blocked by sediment and LWD accumulating at the entrance over the past decade or so. The lower reach of this channel borders the boundary of the Stz'uminus First Nation Squaw-Hay-One administrative boundary located approximately 800 m to 1,000 m downstream, to the northwest.
- Hydraulic effects of this blockage on mainstem channel overbank flooding and erosion potential is uncertain and has not been verified.
- The Reach 1 slope (0.0005 m m^{-1}) is much flatter than upstream resulting in a finer bed texture, and increased deposition of sediment and LWD.
- The position of the channel network is constrained at several locations by the presence of northwest to southeast oriented bedrock ridges in the estuary.

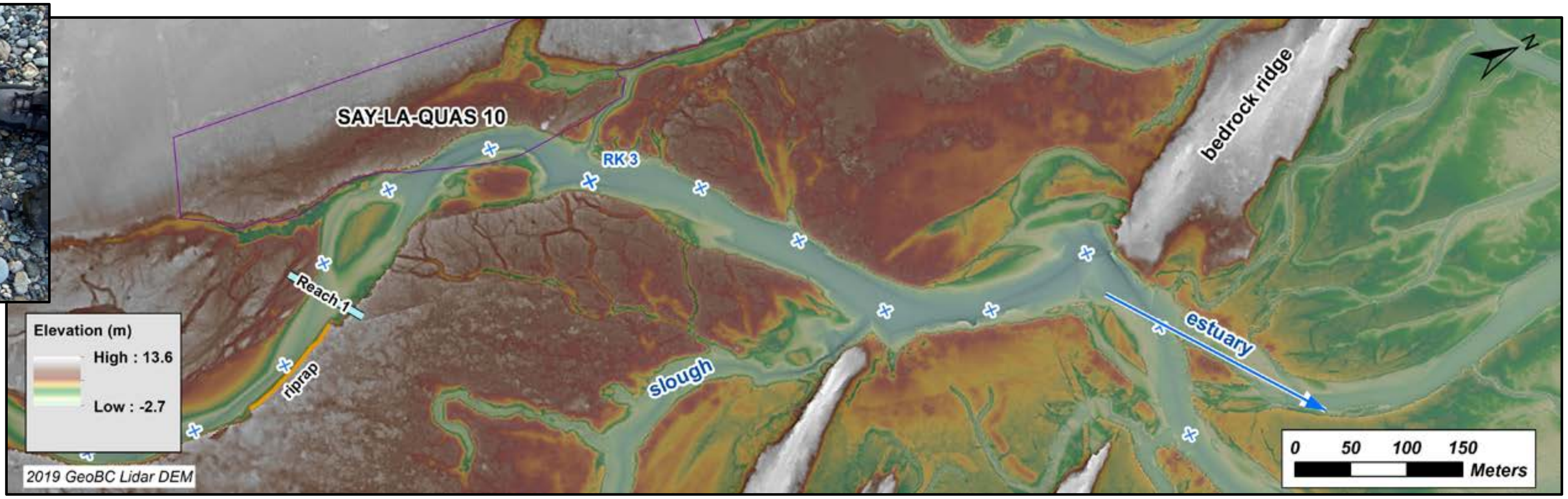


▶ Example of the fine to medium gravels deposited on the bar surface at the pebble count location.

Reach 1	
Reach Length (m)	3,327
Average Slope (m m^{-1})	0.0005
D_{50} (mm)	16
Mean Erosion Rate (m yr^{-1})	-

◀ LWD and sediment accumulation at the head of a distributary channel, viewed downstream toward the mainstem.



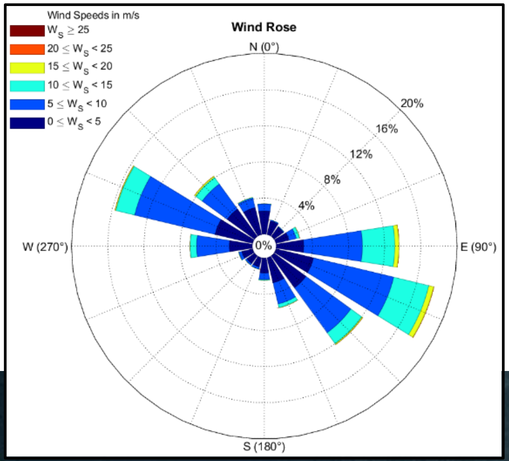


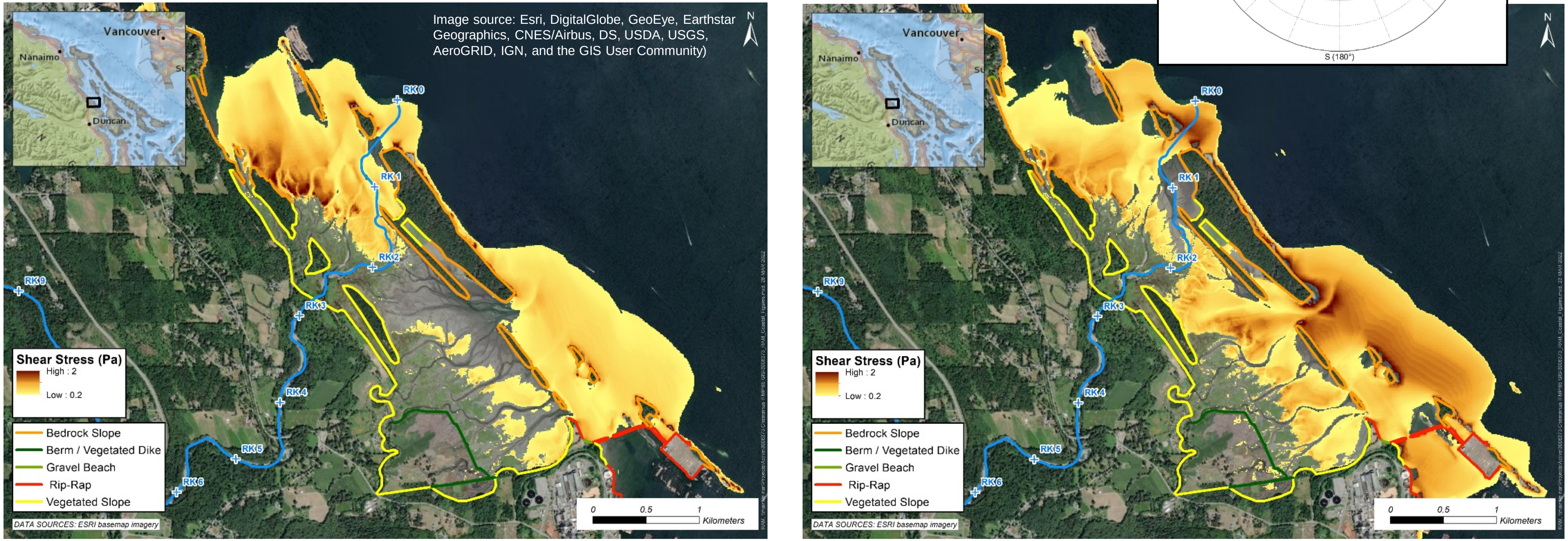
Reach 1 (RK 3.3 to RK 0): The Chemainus River Estuary

The Chemainus River estuary is characterized by a complex channel network distributed across a relatively flat gradient. The low gradient provides an environment whereby avulsions are common, and the channel network is continuously shifting. Combined with tidal influences and riverine processes, wave erosion plays an important role on the dynamics of the Chemainus River estuary.

- The estuary is largely protected from severe winter storms blowing across the Strait of Georgia due to the presence of the Gulf Islands (including Valdes, Thetis, Galiano, and Saltspring Islands). However, significant wind-generated waves are still generated through the Stuart Channel (between the Gulf Islands and Vancouver Island).
- Wind-generated waves produce shear stresses strong enough to mobilize and re-distribute sediment between periods of flooding in the estuary.

▶ Wind rose for Halibut Bank in the Strait of Georgia shows that the region experiences winds oriented largely in the northwest to southeast direction.





▲ Wave shear stress from SWaN model simulations of northerly (left panel) and east-southeasterly (right panel) annual wind events. The northerly wind event produces higher magnitudes of shear stress near the main channel of the Chemainus River, while the east-southeasterly event produces shear stress across a wider area of the estuary. The bedrock and rip-rap shorelines are likely to be resistant to erosion, while the gravel beaches and vegetated slopes are more likely to erode at a higher rate.

8 SEDIMENT MOBILITY AND THE CHANNEL PROFILE

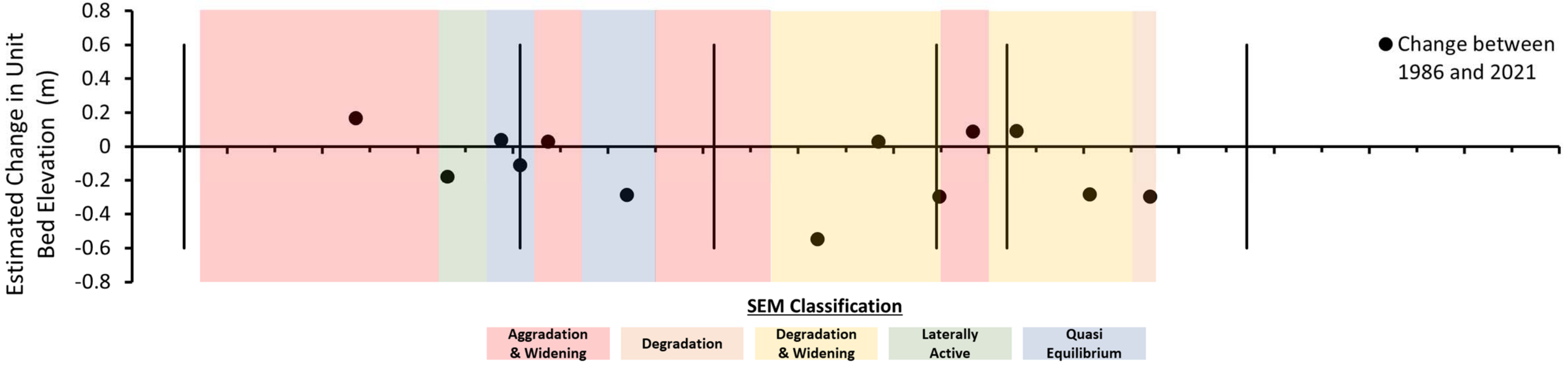
Sediment Accumulation and Channel Profile Changes

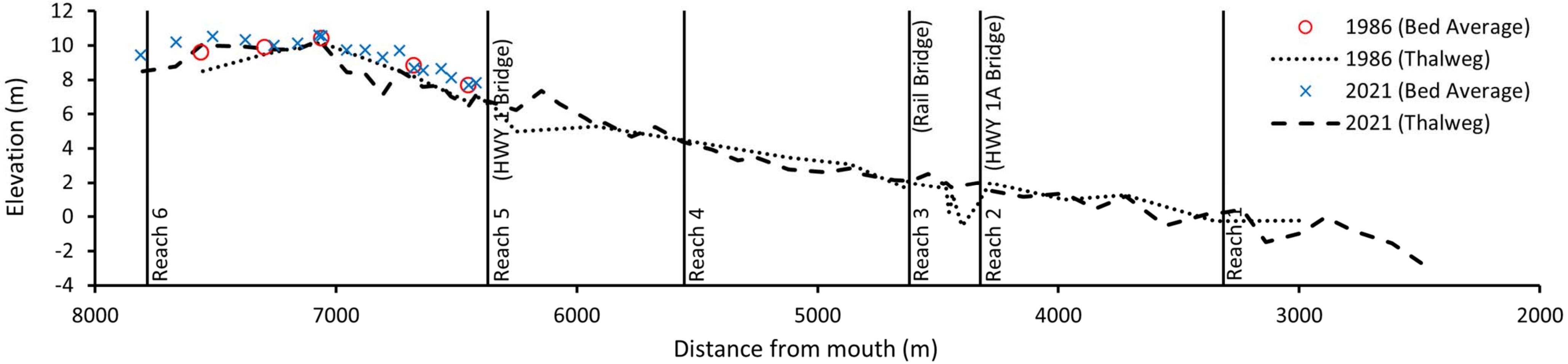
There are several depositional zones along the study reach where sediment and LWD is prone to accumulating. These zones are typically associated with hydraulic controls at bridge crossings, bedrock outcrops, and valley confinement. Sediment accumulation is associated with changes in channel width and bed elevation along the channel profile.

- Reach 6:
  - Aggradation since 1986 is apparent, particularly at RK 7.1.
  - The dominant SEM class (provided by the Cowichan Water Board, 2022) for Reach 6 is aggradation and widening.
- Reach 5:
  - The 1986 to 2021 channel surveys show the thalweg elevation has increased overtime, particularly within a few hundred metres downstream of the Highway 1 bridge. Average bed elevation changes over time within this channel reach are difficult to interpret because of the high degree of lateral instability exhibited over time.
  - The SEM classes for Reach 5 indicate a state of aggradation and widening near the upstream and downstream ends of the reach and a quasi-equilibrium state mid-reach.
- Reach 4:
  - An overall degrading trend is apparent. At RK 5.1, cross-section surveys reveal bed lowering of approximately 0.55 m. This location coincides with the entrance to an old river-bed position south of the modern-day channel, which could be re-opened should the channel erode into its banks (see Page 24 for more details).
  - The SEM classes for this reach shows a transition from aggradation and widening at the upstream end to degradation & widening in the lower 700 m of the reach.
- Reach 3:
  - Aggradation is apparent across the reach, and vertical changes in the thalweg elevation is in the order of 2 m in the reach upstream of the Highway 1A bridge.
  - The dominant SEM class is a state of aggradation and widening.
- Reach 2:
  - Bed lowering is apparent across the reach.
  - The dominant SEM class is a state of degradation and widening.

▼ Plot showing the estimated change in bed elevation between 1986 and 2021 cross-section surveys, overlaid with SEM classes (SEM data provided by the Cowichan Water Board, 2022).

SEM classes reflect the geomorphic condition of the channel. The SEM classes consider the cyclical nature of channel evolution, whereby the channel transitions between periods of aggradation, degradation and quasi-equilibrium.





▲ Plot showing average bed elevation and thalweg elevation data from 1986 and 2021 survey data. Average bed elevation represents the average elevation at each cross section, including the deepest parts of the channel, top of exposed channel bars and all points in between.

8 SEDIMENT MOBILITY AND THE CHANNEL PROFILE

Sediment Mobility

- Plots represent the maximum values for each parameter over the course of an unsteady hydraulic model run of a 350 $m^3 s^{-1}$ discharge flood event ($Q_{reference}$). This reference discharge approximates bankfull flow, the flood condition that forms and maintains the morphology of the current-day channel.
- These plots show hydraulic and sediment mobility parameters extracted from NHC's 2D HEC-RAS model of the river. See accompanying reports for details of hydraulic model development.
- The plotted values represent positions along the channel thalweg. They do not reflect the complex spatial variations across the channel laterally.
- The distribution of grain sizes along the river channel was interpolated from a small sample of surface pebble counts collected by NHC in 2021.
- Sediment grain size data collected by KWL (2021) and CWB (2021) are also presented in the middle plot to the right but were not used to interpolate the downstream trend of grain size along the longitudinal profile. No information on subsurface samples was collected.
- Due to these limitations, inferences on sediment mobility are limited to general trends.

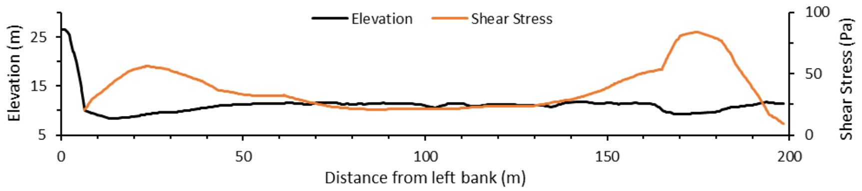
Sediment Transport Parameters

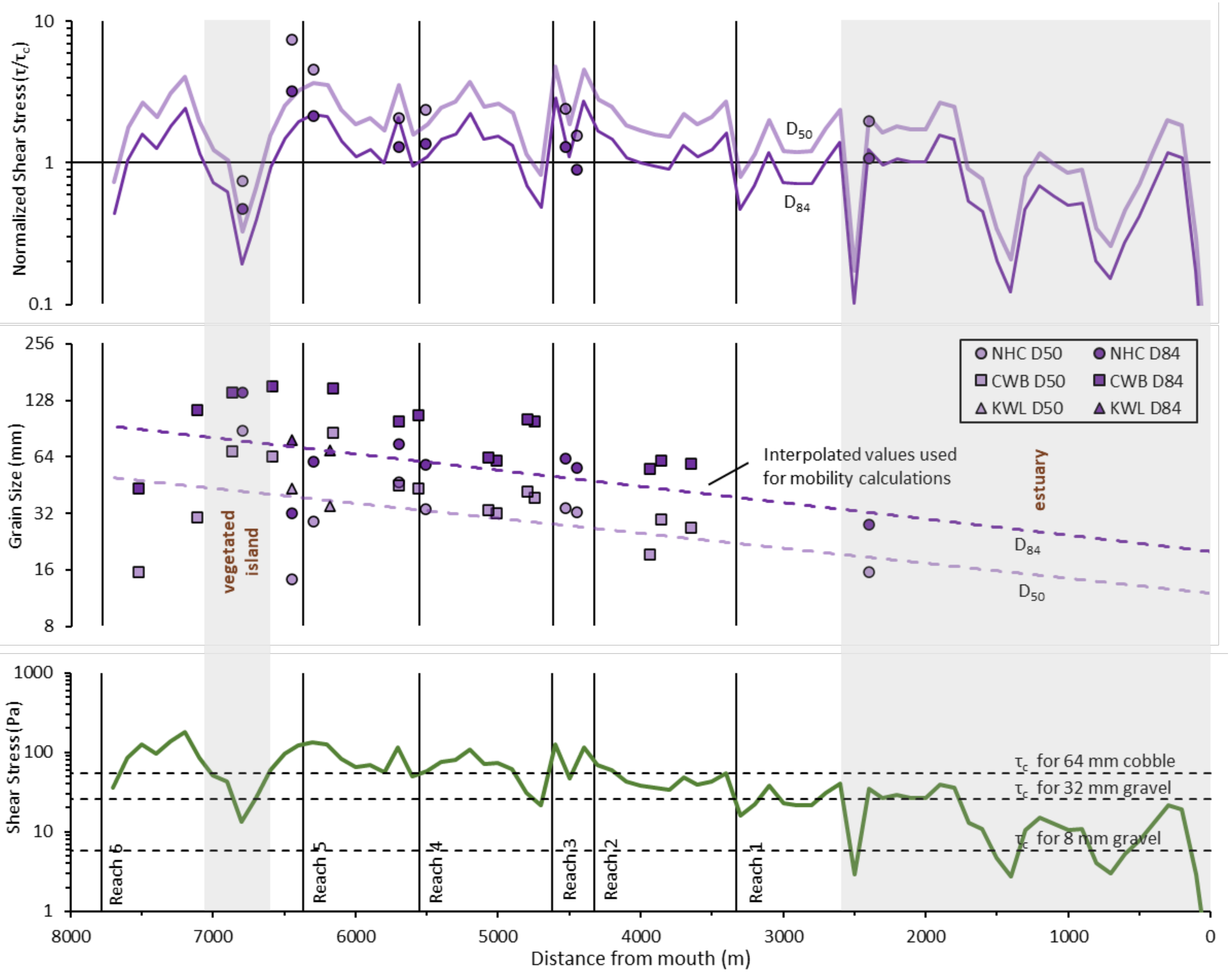
Shear stress (τ): The strength of flow available to move sediment, proportional to flow depth times flow slope.

Critical Shear Stress (τ_c): The shear stress required to move a given size of sediment as bedload.

Shields Parameter (τ^*_c): The ratio of fluid forces tending to initiate particle motion to the gravity force tending to keep the particle at rest. Dependent upon the size of the individual particle, but also the arrangement, shape, and size distribution of the surrounding material. A value of 0.045 is typically used, but values from 0.02 to 0.25 are possible. Larger amounts of sand and finer subsurface material promote lower values of τ^*_c.

- Based on the simulated flood event, the Chemainus River is capable of transporting cobble-sized sediment through Reaches 6 to 3, downstream of which the shear stress drops below the threshold required to move this caliber of sediment.
- Medium to coarse gravel may be transported to the top of the estuary (around RK 1.7), downstream of which only finer sediment is mobile.
- At approximately RK 6.7 to RK 7.1, there is a dip in shear stress. This coincides with the location of a large vegetated island in Reach 6, where flow splits into two channels. The variation of shear stress across the two channels is shown below at RK 6.9.





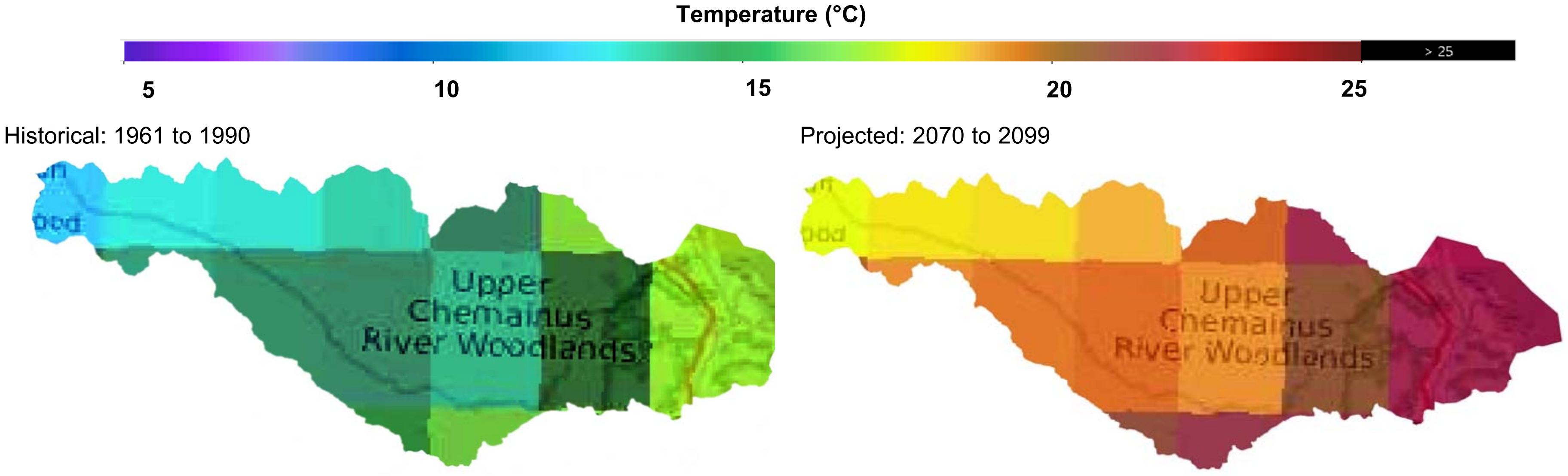
9 ALTERED CONDITIONS

Hydroclimate

In the context of ongoing climate change in British Columbia, we can expect to see changes in environmental conditions (APEGBC, 2017). Under existing or altered hydroclimatic conditions, physical changes may occur to the landscape that induce a longer-term geomorphic response that will alter how the watershed and floodplain responds to floods.

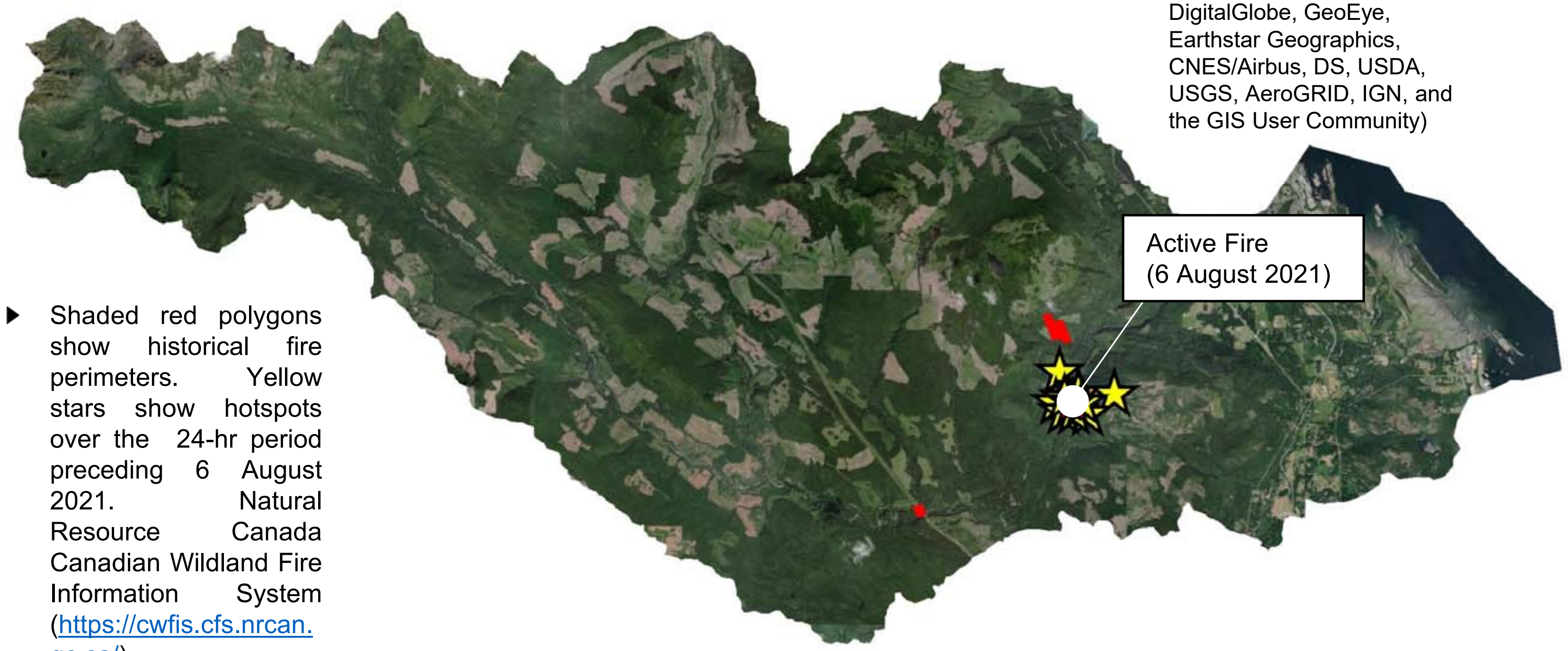
Altered hydroclimatic conditions may induce the following geomorphic responses:

- Sea level rise (SLR) will alter the upstream extent that the stream channels are influenced by tides, alter the pattern and position of estuary distributary channel formation, and will expose areas farther inland to coastal processes (see Page 36).
- Increasing summertime temperatures could result in more frequent and larger fires. Increasing winter temperatures could result in adverse conditions for forest health, such as insect infestation:
    - Fires can have both immediate and long-term hydrologic effects. Disturbance effects include relatively short-term soil hydrophobicity, which increases runoff rates (Winkler et al 2010); longer-term effects to runoff patterns as a result of altered tree canopy. Similarly, altered rates of transpiration and interception of precipitation by the tree canopy as a result of insect infestation may lead to altered soil moisture conditions, snowmelt patterns, and streamflow patterns (Pike et. al. 2010).
    - The post-event landscape can have an altered effective erodibility of the landscape. Over time, deadfall and debris accumulation on steep slopes, gullies, and stream channels may increase the potential for high energy hydrogeomorphic events such as debris floods or debris flows and channel sedimentation (Pike et. al 2020).
    - Depending on the spatial extensiveness of the event, the effects may be relatively localized or at a watershed-scale. Accumulation of debris and sediment can sometimes continue for several years, with a geomorphic response that persists for longer than the immediate hydrologic impacts.
    - Riparian vegetation succession patterns could influence channel resistance to bank erosion, LWD recruitment patterns and potential for channel form changes.



▲ Projected Summer Temperatures (for June, July, and August, from Pacific Climate Impacts Consortium, PCIC). The PCIC Plan2Apapt tool generates maps describing projected future climate conditions for regions throughout BC based on a standard set of climate model projections (https://services.pacificclimate.org/plan2adapt/app/).

Image source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus, DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community)



▶ Shaded red polygons show historical fire perimeters. Yellow stars show hotspots over the 24-hr period preceding 6 August 2021. Natural Resource Canada Canadian Wildland Fire Information System (https://cwfis.cfs.nrcan.gc.ca/).

9 ALTERED CONDITIONS

Sediment Supply

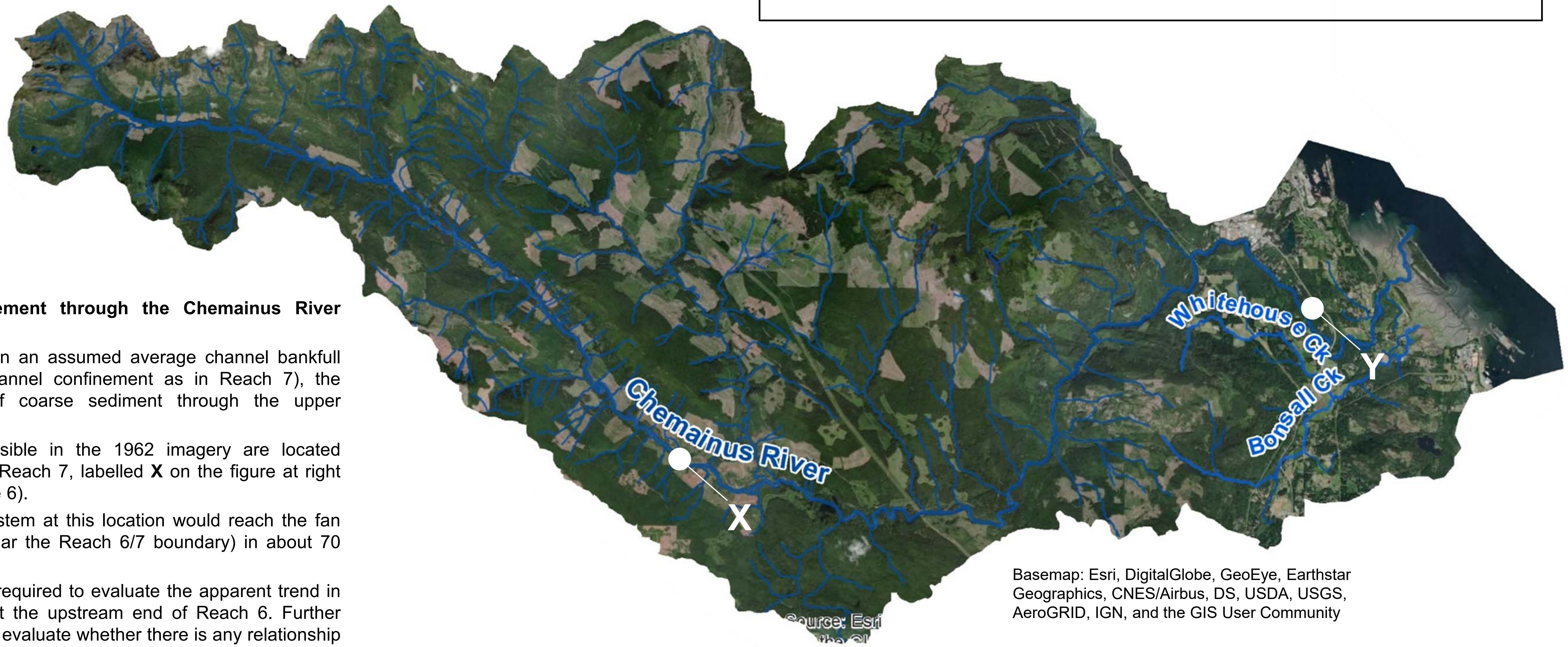
Over a time-scale of decades to centuries, sedimentation rates and patterns at the alluvial fan are a function of the supply of sediment from the watershed slopes to the mainstem and tributary channels, degree of lateral channel stability, and relative rate of sediment transport and storage within the active channel.

Altered sedimentation patterns and rates on the alluvial fan may induce channel geometry and profile changes. Altered conditions on the fan could increase the geomorphic hazard potential on the MVB.

Legacy effects of historical forestry activities that started in the 1800s has altered the pattern of coarse sediment supply to the alluvial fan on the floodplain.

- Once introduced into the mainstem channel, coarse sediment can take many decades to reach the alluvial fan.
- The movement of coarse sediment through the system can be modelled following Beechie (2001) based on an annual travel distance (L_b) as a function of bankfull channel width w_{bf}:

$$L_b = -32 + 21 \times w_{bf}$$



Basemap: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus, DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Example concept: sediment movement through the Chemainus River watershed:

By applying Beechie (2001), based on an assumed average channel bankfull width of 37 m (assuming similar channel confinement as in Reach 7), the estimated annual travel distance of coarse sediment through the upper watershed is 745 m/year.

- Slide pathways and cutblocks visible in the 1962 imagery are located approximately 50 km upstream of Reach 7, labelled **X** on the figure at right (The 1962 image is shown on Page 6).
- Sediment entering the channel system at this location would reach the fan apex (labelled **Y** on the figure, near the Reach 6/7 boundary) in about 70 years.
- More survey monitoring would be required to evaluate the apparent trend in average bed elevation changes at the upstream end of Reach 6. Further investigations would be required to evaluate whether there is any relationship between the apparent aggrading trend at this location and legacy effects of historical forestry activities (plotted bed elevation changes at this location are shown and discussed on Pages 15 and 31).

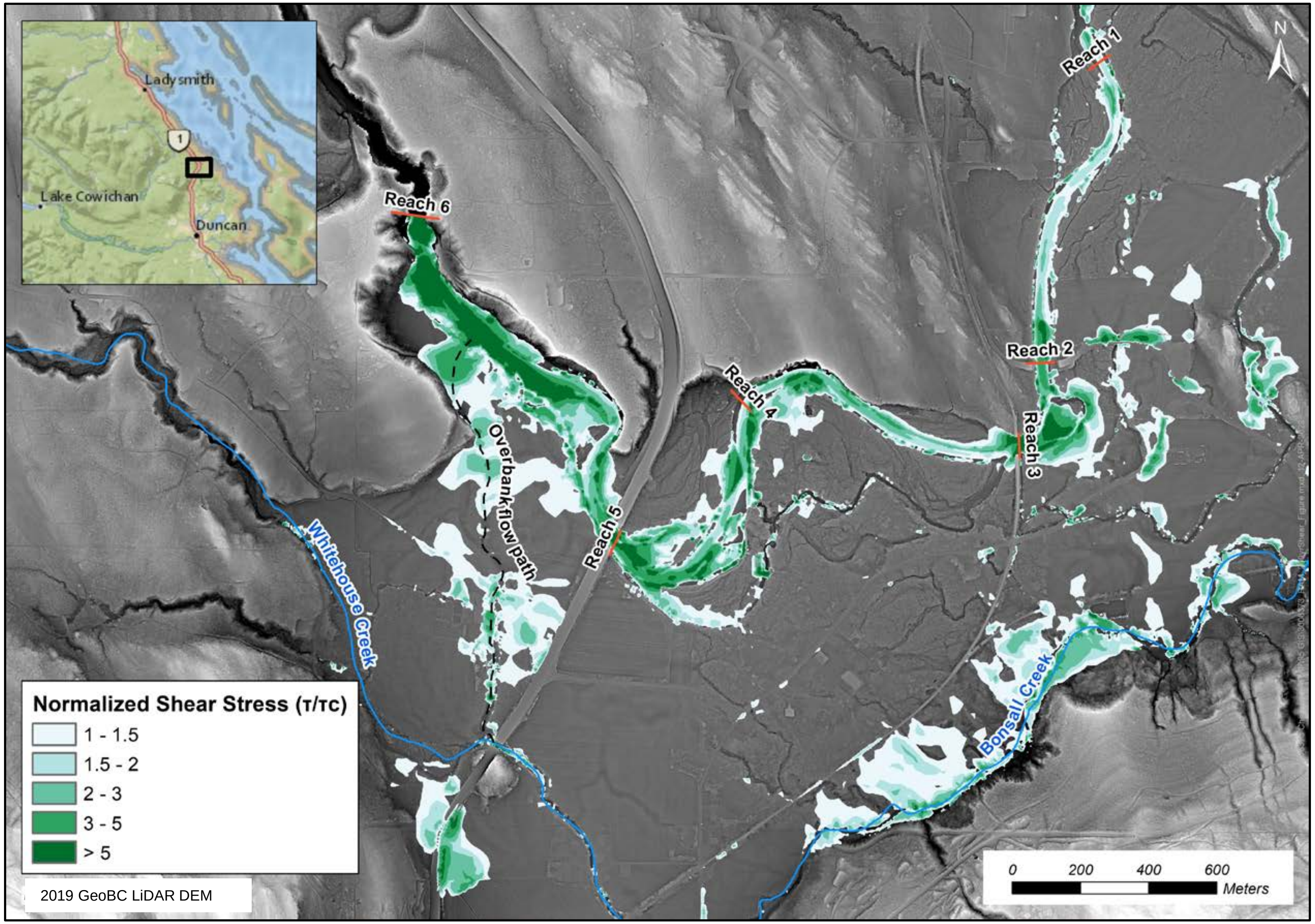
Flow Regime

In the context of ongoing climate change in British Columbia, the morphology of the Chemainus River will evolve and adapt to the altered hydroclimatic regime. Therefore, changes in the magnitude and recurrence of peak flood events may lead to adjustments in channel form.

- The map panel to the right illustrates the spatial pattern of shear stresses produced by a 2D HEC-RAS hydraulic model simulation of a 0.5% annual exceedance probability flood (i.e., 200-year recurrence interval flood), with a 20% increase in discharge to account for climate change. The darker shades of green represent areas of higher normalized shear stress and, thus, higher potential for sediment transport.
- For in-channel areas, a normalized shear stress value around 1 implies incipient motion of sedimentary particles on the bed. As the normalized stress increases to around two or more, we expect to see full transport of bed material.
- Outside the channel, the floodplain may scour in areas experiencing high shear stress values during the simulated 0.5% annual exceedance probability (AEP) flood. The patterns in floodplain shear stress reveal preliminary insights into preferential overbank flow paths and potential locations where channels may form during an extreme flood event.
- In Reach 6, a low-lying area on the floodplain south of the present-day channel experiences high shear stress during the modeled event. This channel ultimately delivers flow south into Whitehouse and Bonsall Creeks. Hence, an increase in the amount of flow through this area has direct implications for the stability of these creeks.
- Overbank flow spilling out from Reach 6 may also drain towards the upstream edge of Highway 1, inducing the potential for scouring along the road prism. In the absence of relief structures that allow flow to drain downstream of Highway 1, water may be carried parallel to the road and lead to sediment deposition and aggradation.

This section summarizes some of the potential responses of the channel to an extreme flood event. However, an important driver of morphological changes over time and channel form are the more moderate and more frequent events, such as the bankfull discharge (Wolman and Miller, 1960).

Changes in the channel width and pattern in response to climate change is described in more detail on Page 42.



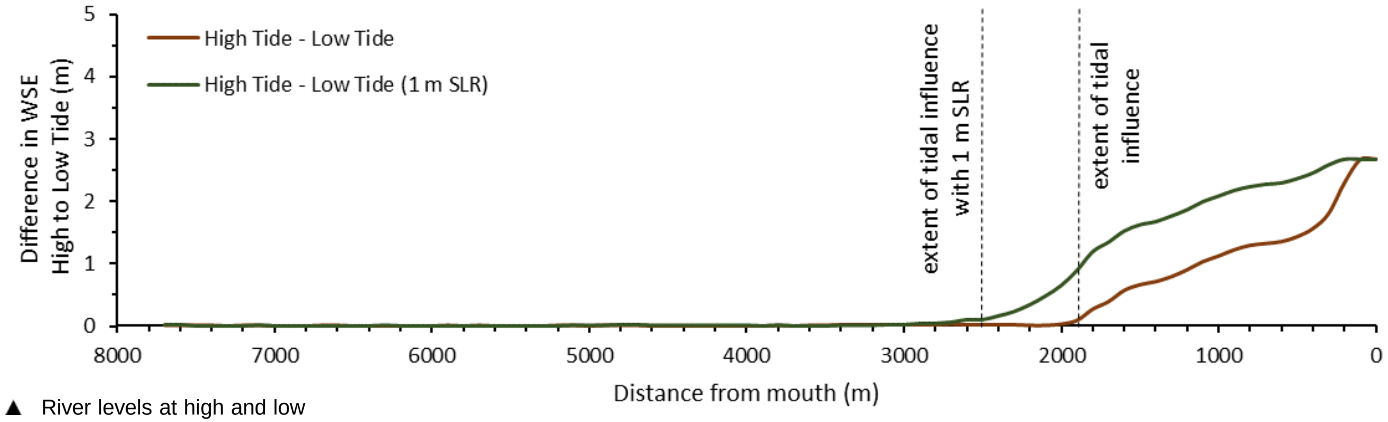
▲ The normalized shear stress produced during a 2D HEC-RAS hydraulic model simulation of a 0.5% AEP flood with a 20% increase in discharge to account for climate change. Normalized shear stress is calculated as the ratio of shear stress (τ) to critical shear stress (τ_c) for sediment entrainment. Here, a critical shear stress of 25 Pa was used, an approximate threshold for mobility of coarse gravels (USGS, 2013).

Base Level Changes

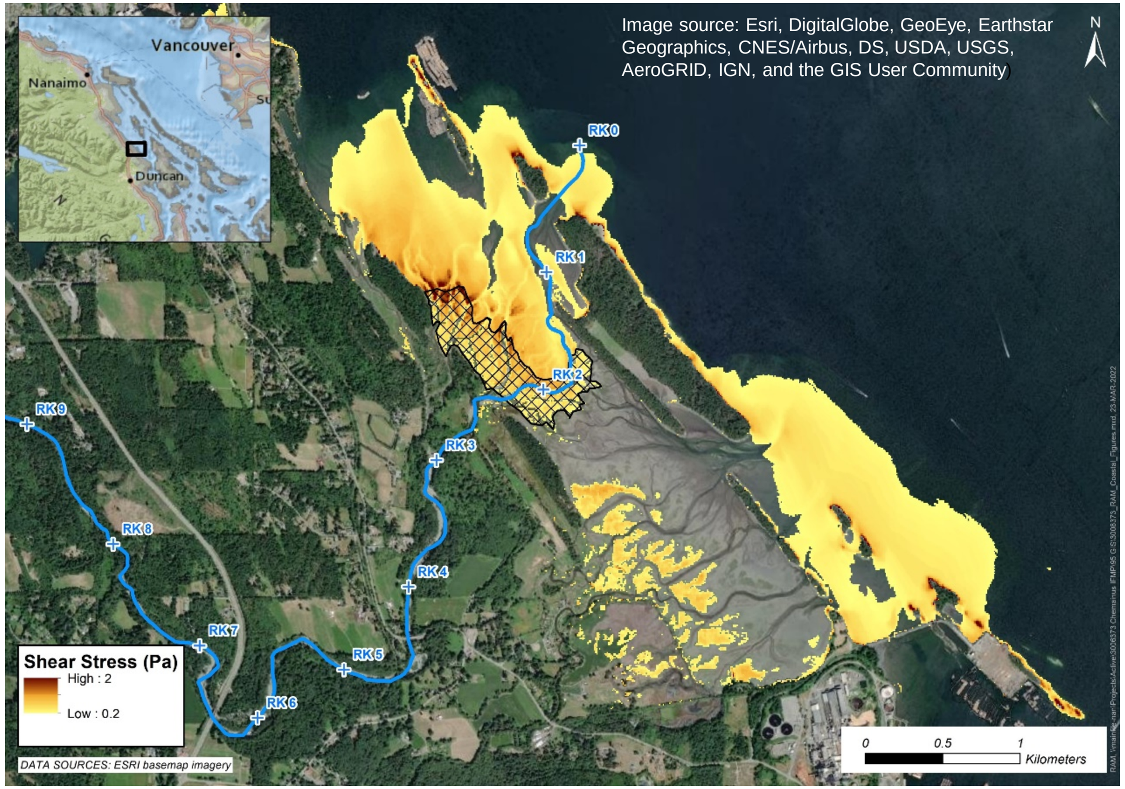
The base level is defined as the limit below which a stream cannot erode. For the Chemainus River, this occurs as the river enters the ocean, whereby the stream's velocity is reduced losing its erosive power, and sediment is deposited.

- Climate-change induced SLR will produce a change in the base level of the Chemainus River. Rivers may respond in many ways to a higher future base level, including aggradation and adjustments to the channel profile, altered sediment mobility patterns and sediment grain sizes, changes in channel planform, increasing bed roughness, or a combination of these (Schumm, 1993).
- The morphological response of the Chemainus River to SLR may take place over a long period of time (multi-decadal-scale). A 1 m SLR will cause the extent of tidal influence to migrate approximately 600 m upstream, based on hydraulic simulations with bankfull ($Q_{reference}$) riverine flow combined with a mean tide. Tidal effects with SLR may extend farther upstream under different tide and river flow conditions. As the tidal influence extends farther upstream, an increased potential for channel aggradation may induce more frequent channel avulsions (Jerolmack, 2009).
- SLR affects the spatial pattern of shear stress produced by waves such that patterns of erosion and deposition along the coastal fringe zone will be altered.
- Salt-water intrusion may alter the shoreline and lowland biota, which would influence channel resistance to bank erosion and potential for channel form changes.

▲ Photo looking north over the Chemainus River Estuary (CVRD photo).



▲ River levels at high and low tide based on the mean annual tide and bankfull flow conditions ($Q_{reference}$). WSE = water surface elevation.



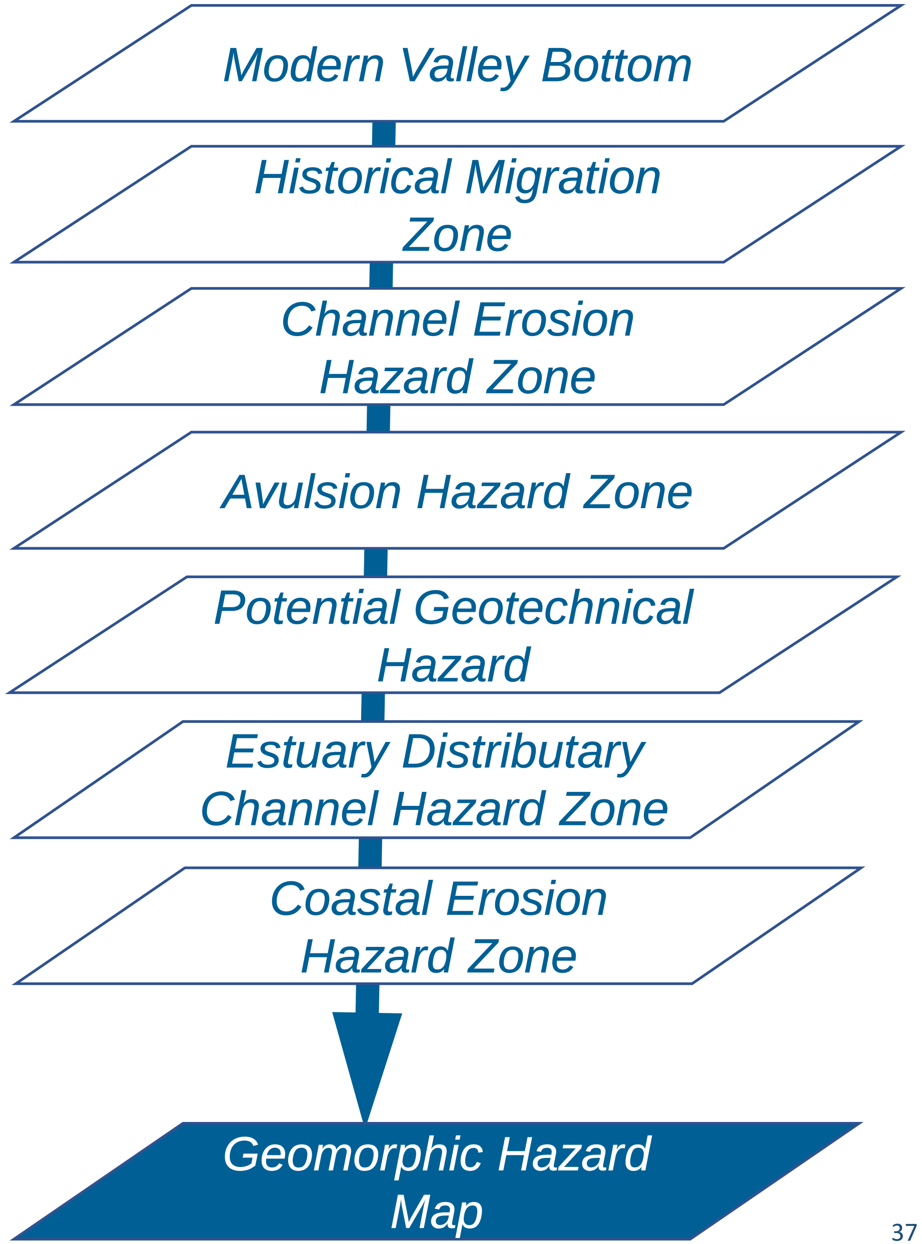
▶ Simulating Waves Nearshore (SWaN) model simulations of wave shear stress for a northerly wind event with 1 m SLR and Higher High Water Meant Tide. Only shear stress values greater than or equal to 0.2 Pa are presented, representing an approximate threshold required to mobilize sand-sized sediment.

The black cross-hatched polygon represents the primary area where shear stress is high enough to mobilize sand in the 1 m SLR scenario, but not during present-day conditions. This highlights the potential for the area affected by wave erosion to migrate upstream under a climate change scenario.

Geomorphic Hazard Map Elements

The framework for defining geomorphic hazard zones for this project was adapted and modified from approaches used in Washington state (see Page 1). A 60-year planning horizon was selected based on the long -life design service life category defined in the BC Housing Design Guidelines and Construction Standard (BC Housing 2019).

ZONE	HAZARD DEFINITION
Modern Valley Bottom (MVB)	Area where channel migration has likely occurred in the past several thousand years and is susceptible to occurring under the present-day hydroclimate regime.
Historical Migration Zone (HMZ)	Area that the channel occupied in the historical record, based on available imagery and survey data. This area is also susceptible to erosion and avulsion hazards.
Channel Erosion Hazard Zone (EHZ)	Area at risk to bank erosion by stream flow over a 60-year planning horizon. This area is also susceptible to avulsion hazards.
Avulsion Hazard Zone (AHZ)	Area that is at risk to avulsion over a 60-year planning horizon. This area may also be susceptible to estuary distributary channel hazards in tidally influenced areas. The AHZ is classified into two categories (after Nanson and Knighton 1996): • First-order avulsion: sudden and major shift to a new part of the floodplain • Second-order avulsion: sudden reoccupation of an old channel on the floodplain. Second-order avulsion zones may also be subject to First-order avulsions.
Potential Geotechnical Hazard (Unrated)	Area with steep slopes within the erosion hazard zone or avulsion hazard zone, which may become geotechnically unstable due to inundation or erosion of the toe of the slope. A geotechnical assessment is required to determine an appropriate geotechnical setback for land that may potentially be subject to any potential geotechnical hazards. Only steep slopes within 10 m of the erosion hazard zone boundary were flagged as potential geotechnical hazards. Additional steep slope hazards not flagged may exist outside of the erosion hazard zone.
Estuary Distributary Channel Hazard Zone (DHZ)	Relatively lower gradient area influenced by tidal processes and susceptible to the formation of distributary channels. This area is also at risk to channel erosion and avulsion hazards.
Coastal Erosion Hazard Zone (CHZ)	Landward extent of area likely to be susceptible to erosion from tidal currents and waves generated during coastal storms, with 1 m sea level rise. This area is also susceptible to erosion, avulsion, and estuary distributary channel hazards.



10 GEOMORPHIC HAZARD MAPPING

Geomorphic Hazard Mapping Criteria

The framework for determining geomorphic hazard zones for this project was adapted and modified from approaches used in Washington state (see Page 1).

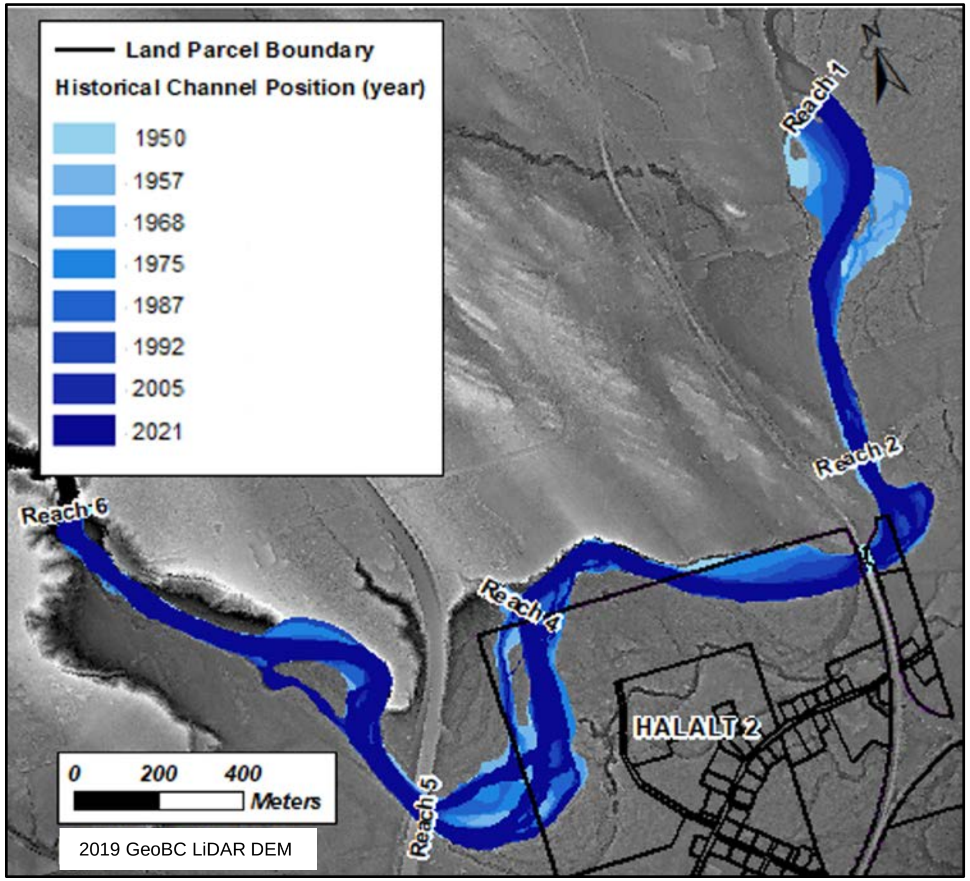
ZONE	METHOD OF DETERMINATION
Modern Valley Bottom (MVB)	Interpretation of local geology information; and DEM topography and terrain information.
Historical Migration Zone (HMZ)	Interpretation of historical imagery (air photos, Google Earth imagery, and orthophotos) spanning a 71-year time period (1950 to 2021) and an 1877 survey of riverbed locations within the Halalt First Nation administrative boundary (see Pages 39 and 40).
Channel Erosion Hazard Zone (EHZ)	Calculated reach-averaged erosion rates and maximum measured erosion rates on a reach-by-reach basis. Application of maximum versus reach-averaged erosion rates were applied according to the rules outlined in Erosion Buffer Rules table on Page 41. Regime channel width changes associated with climate change effects have been incorporated according to the approach outlined on Page 42.
Avulsion Hazard Zone (AHZ)	Post-2021 flood channel assessment, documented evidence of historical avulsions, interpreted 2D HEC-RAS hydraulic model simulation results, calculated channel superelevation and slope ratio between potential avulsion paths and the existing channel (see Page 43).
Potential Geotechnical Hazard Zone (Unrated)	Interpreted from existing terrain, but not mapped or assessed in detail; a geotechnical study is recommended to refine the assessment of geotechnical hazards.
Estuary Distributary Channel Hazard Zone (DHZ)	Interpreted historical imagery (air photos, Google Earth imagery, and orthophotos) spanning a 71-year time period (1950 to 2021) and interpreted observations of tidal influence and 2D HEC-RAS hydraulic model simulations of tidal influence with 1 m sea level rise.
Coastal Erosion Hazard Zone (CHZ)	Interpreted area exposed to wave induced shear stresses, from SWaN model simulations of annual northerly and east-southeasterly wind events, based on 1 m sea level rise.

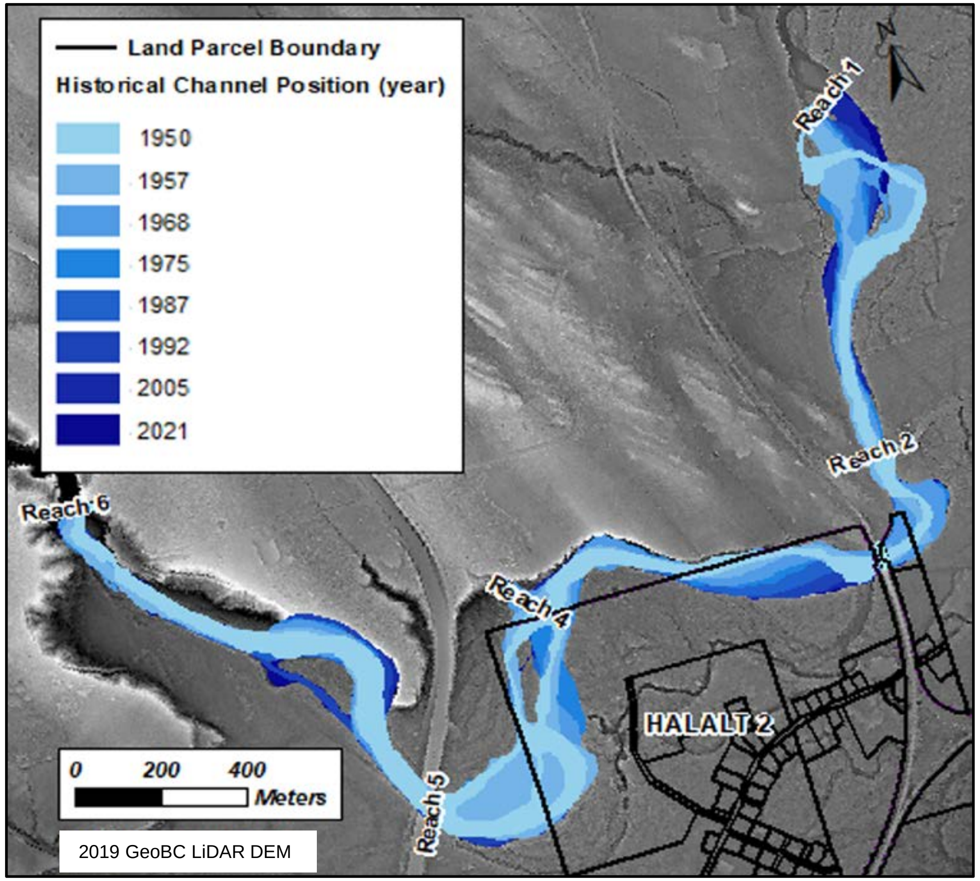
Historical Channel Migration Zone (HMZ) Mapping: Channel Position

Historical Channel Migration Mapping

- Historical channel positions were determined by delineating bank lines based on an assessment of georeferenced historic imagery.
- Historical air photos were available and analyzed for 6 years between 1950 and 1992.
- Two additional years of historical imagery were also analyzed: Google Earth imagery from 2005 and orthophotos from 2021.
- In total, bank lines were delineated based on 8 years of historic imagery spanning a 71-year period (1950 to 2021).

- The southern channel that flows along the island in Reach 6 has become more prominent over time, with flow being primarily directed along the northern main channel in 1950 (light blue) and flow splitting across the northern and southern channels in more recent years (dark blue).
- Near the downstream end of Reach 4, the channel has progressively migrated southwards throughout the air photo period of record (1950 to 2021).
- Outward migration of the meander bend at Reach 3 is apparent from the historical channel mapping. A bedrock outcrop along the downstream end of the outer bend provides increased resistance to erosion. At the upstream end of the outer bend, riprap is present, although there are signs of scour along the toe.
- At the downstream end of Reach 2, the channel avulsed westward between 1950 and 1957. Since 1975, the channel has been progressively migrated eastward along the at channel bend at this location.

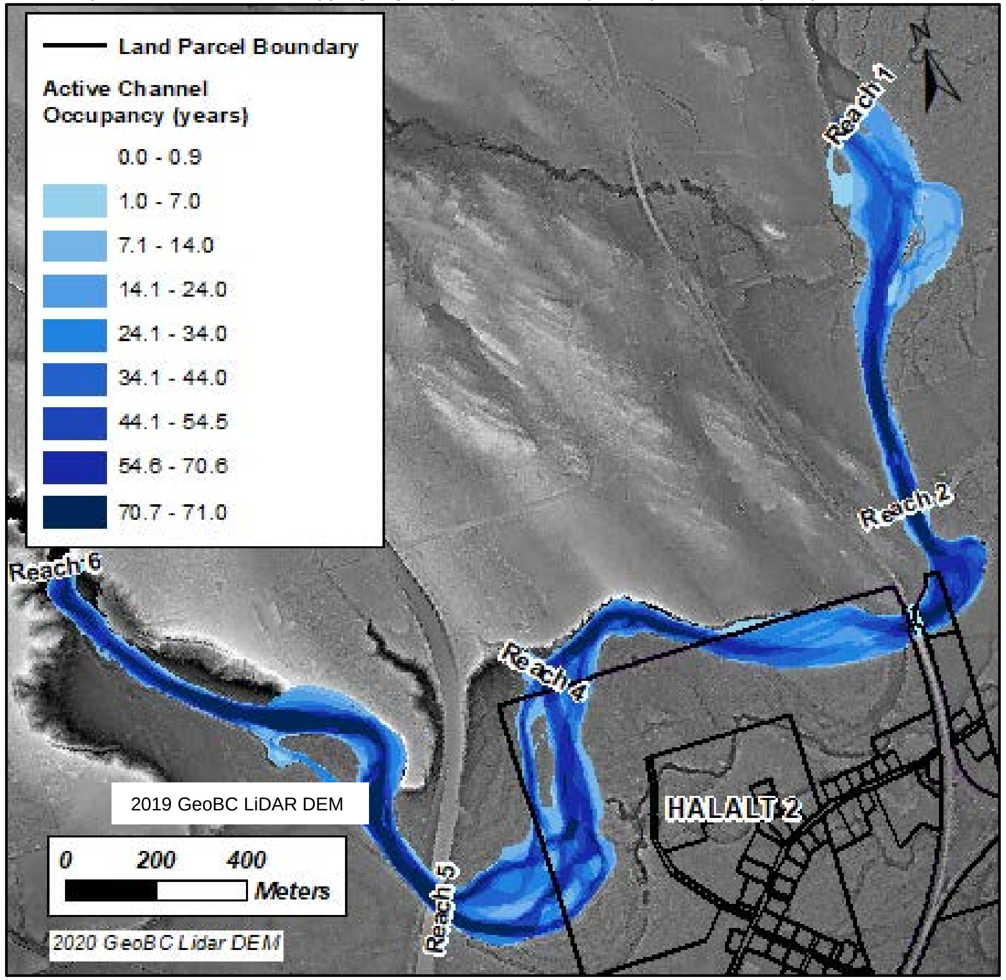




- Historical channel position based on analysis of historical imagery, with the channel positions overlaid from oldest to most recent (left) and most recent to oldest (right).

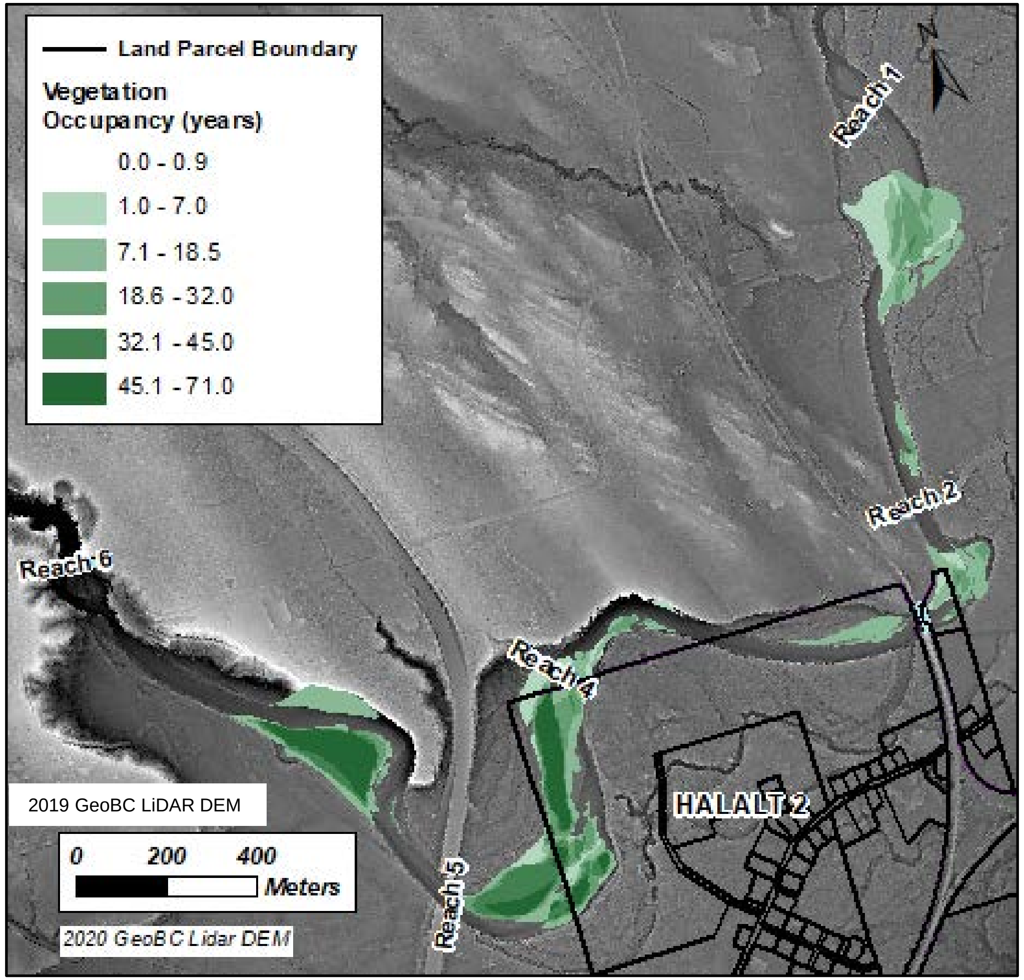
Historical Channel Migration Zone (HMZ) Mapping: Channel Occupancy

- Greater lateral stability (darker shades of blue) is observed in the straighter portions of Reach 2 and Reach 6, and along the erosion-resistant bluffs in Reach 4. At these locations, the channel has occupied the same path for much (55 to 71 years) of the air photo period of record.
- At the outer channel bends in Reach 5, Reach 3, and Reach 2 there has been more lateral instability (lighter shades of blue), with the channel occupying a given path for fewer years (ex. 1 to 14 years).



▲ Map of historical channel occupancy based on analysis of historic air photos.

- Prominent vegetated features have been present for much (45 to 71 years) of the air photo period of record in Reach 6 (upstream of the HWY 1 bridge) and in Reach 5 (downstream of the HWY 1 bridge).
- At channel bends in Reach 3 and Reach 2 there are more dynamic vegetated features. At these locations loss and regrowth of vegetation has occurred, corresponding to lateral instability of the channel.



▲ Map of historical occupancy of vegetated bars and islands based on analysis of historic air photos.

Erosion Hazard Zone (EHZ) Mapping: Buffer Rules

The Erosion hazard buffer width was based on the maximum erosion buffer and reach-averaged buffer as described in the table below. Estimated regime channel changes associated with climate change induced increased peak flows have been incorporated into the EHZ (described on Page 42).

Interpreted Channel Bank Material	Susceptibility to Erosion Historically (1950 – 2021)	Channel Geomorphology	Erosion Hazard Buffer
Alluvium	High	Some combination of: - Highly erodible bank material - History of channel instability observed in air photo record; -Evidence of geomorphic processes that suggest potential future instability	Maximum erosion buffer *or* probability-based maximum erosion buffer
	Low	Some combination of: - Somewhat erosion-resistant bank material; - History of channel stability observed in air photo record; - Evidence of geomorphic processes that suggest decreased risk of instability	Reach-averaged buffer increased by erosion-resistant percentage of the reach
Bedrock	Low	-	Reach-averaged Buffer
Riprap or concrete	-	-	Either reach-averaged buffer increased by erosion-resistant % of Reach *or* maximum erosion buffer, *or* probability-based maximum erosion buffer depending on channel geomorphology (refer to rules described for alluvium)
Bluffs (till/glacio-marine clay)	Low	Channel directly impinges on bluffs	Reach-averaged buffer
		Channel is offset from bluffs; bank material is alluvium	Reach-averaged buffer increased by erosion-resistant percentage of the reach

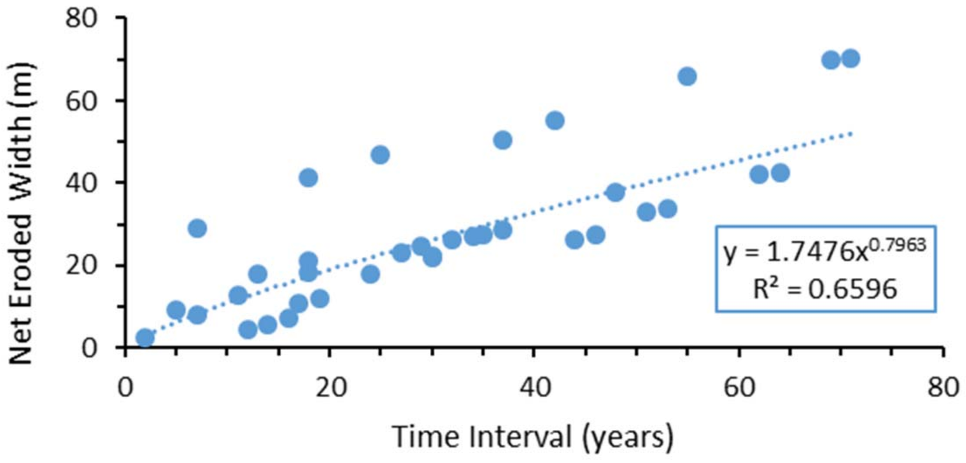
Erosion Hazard Buffer Metrics

Maximum erosion buffer: width is derived from the maximum erosion rate over the air photo period of record, applied over a 60-year time interval

Reach-averaged buffer: width is calculated by interpolating the average eroded width for a 60-year time interval. Average eroded widths were calculated based on an analysis of areal change over the 71-year air photo period of record

Probability-based maximum erosion buffer: width is derived from a probability-based approach incorporating survey data. The probability-based approach was only applied along the right bank in the upstream portion of Reach 5, and survey data collected before and after the November 2021 flood was used. A probability analysis, performed based on the historic flood record, indicated a 92% chance of an event of that magnitude occurring no more than 6 times over a 60-year interval. The eroded width associated with the November 2021 flood and the calculated annual average erosion rates were proportionally applied over a 60-year time horizon to project the erosion buffer.

▸ Graph of average eroded width for Reach 2 over the 71-year air photo period of record calculated based on areal changes in the active channel. The rate of change fits a power function, in which the magnitude of change decreases with increasing duration. Over a given flood event, the active channel may erode floodplain that was previously unoccupied over the period of record. However, over time, the channel re-erodes areas historically occupied by the channel.



Regime Modelling

Rational regime theory for alluvial rivers is based on the concept that the width, depth, and gradient of a river channel are determined by the range of flows to which it is subject and by the grain-sizes and supply of channel bed-sediment from the watershed. The bankfull discharge is often viewed as a flow condition that has a strong influence on the channel form. Adjustments in the magnitude of this channel-forming discharge are anticipated to induce changes in the river geometry (i.e., an increase or decrease in channel width, depth, or gradient).

The erosion hazard boundary delineated for the geomorphic hazard map accounts for the potential for morphological changes in response to the anticipated increase in the magnitude of peak flows associated with climate change in British Columbia. For this study, a regime modeling approach was adopted using the physics-based UBC Regime Model (UBCRM), and the bankfull discharge has been approximated using a reference discharge, $Q_{reference}$, of 350 $m^3 s^{-1}$.

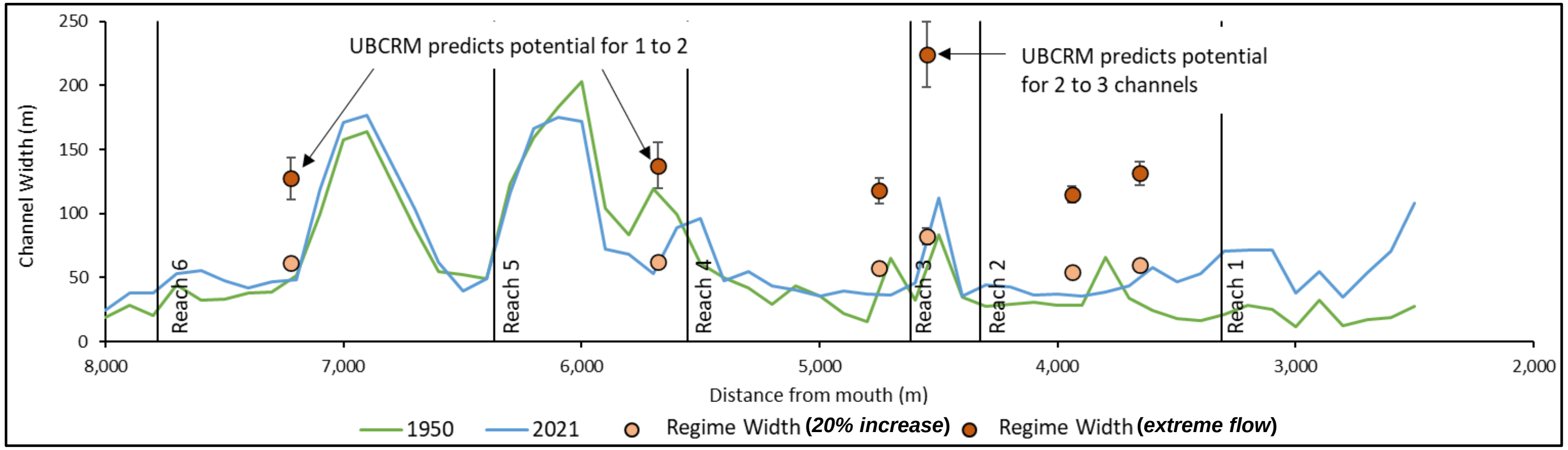
The UBCRM predicts channel form as controlled by the following input parameters: channel-forming discharge, energy gradient slope, bed material grain size distribution, and strength of the channel banks. The model builds on a long history of previous work focused on developing 'regime curves' that relate channel geometry to the channel-forming discharge (U.S. Army Corps of Engineers, 1994).

The UBCRM was calibrated to the 2019 DEM channel geometry by applying the channel forming discharge ($Q_{reference}$) and estimating the distribution of bed sediment from NHC's 2021 pebble counts and data provided by KWL (2021) and CWB (2021).

After the model was calibrated, it was run a second time to determine the regime channel dimensions associated with a 20% increase in the channel-forming discharge, accounting for climate change projections (laballed as *20% increase*). A final iteration of the UBCRM was run using a 0.5% AEP flood event with a 20% increase in discharge to account for climate change to assess the potential channel geometry produced from this extreme flow event (labelled as *extreme flow*).

- Longitudinal profile plot of the UBCMRM results showing predicted channel width and number of channels for two flow scenarios.

  Channel widths measured from 1950 air photos and 2021 orthophotos are shown for reference.



The UBCRM predicts that the river will widen by 6 to 11 m in response to an increase of 20% in the channel forming discharge ($Q_{reference}$). This falls within the projected erosion hazard area buffers, as depicted in the geomorphic hazard map (Page 44).

Channel widening near areas adjacent to low-lying floodplain channels (e.g., the Halalt rearing channel in Reach 6) may increase the potential for a future channel avulsion should these channels become more directly exposed to high velocity flows.

The future conditions 0.5% AEP flood event is likely to fundamentally alter the morphology of the lower Chemainus River. The UBCRM predicts increases in channel width ranging from 50 to 150 m, with multi-thread channel configurations becoming the preferred channel geometry within Reaches 3, 5, and 6. These predictions also provide supporting evidence for the high susceptibility of the Chemainus River floodplain to channel avulsions during extreme flows.

Assumptions and Limitations

The UBCRM assumes, rather conservatively, that the regime flood event is sustained for a sufficient time period to allow the channel to adjust its geometry accordingly. However, extreme flows may be briefer than the duration needed to produce significant morphological adjustments, and changes in channel width may be less than predicted.

The UBCRM also relies on the assumption that channel form is a product of fluvial processes. This assumption cannot be applied to the lower portion of the channel, where tidal backwatering affects upstream channel hydraulics, sediment transport, and channel form. In consideration of this, regime channel analysis focused upstream of Reach 1.

10 GEOMORPHIC HAZARD MAPPING

Avulsion Hazard Zone (AHZ) Mapping

- Several potential avulsion nodes (i.e., channel locations where an avulsion could occur) were identified based on the following criteria:
    - Analysis of historical avulsions
    - Interpreted 2D HEC-RAS hydraulic model results (water surface elevation, shear stress, depth, velocity, and overbank flow paths)
    - DEM analysis and interpretation of relic channel pathways
    - Assessment of the post-2021 flood channel assessment
    - Identified historical sediment and LWD accumulation zones, and evaluation of the potential for reduce hydraulic conveyance or channel-blockage
- Avulsion hazard metrics, including super-elevation, normalized super-elevation, and slope ratio (see avulsion hazard metrics box on right), were calculated for several selected potential avulsion paths using an approach adapted from NHC (2015b).

The avulsion hazard zone is classified into two broad categories, as presented on Page 44):

- First-order avulsion: sudden and major shift to a new part of the floodplain
- Second-order avulsion: sudden reoccupation of an old channel on the floodplain.

▼ Table of Avulsion Hazard Metrics for six selected paths for which avulsion hazard metrics were calculated. Cells shaded in yellow suggest that an avulsion may occur at those locations. A broader assessment of the area indicates that potential avulsion paths are not limited to these four paths and avulsion hazards exist throughout much of the floodplain.

Avulsion Node	River Kilometer (Km)	Normalized Super-elevation (m)	Slope Ratio (Bed elevation, m)
A	7.4	0.3	3.9
B	6.2	0.6	2.5
C	5.9	1.3	0.0
D	5.5	0.1	2.0
E	4.5	0.2	3.5
F	4.2	0.3	5.4

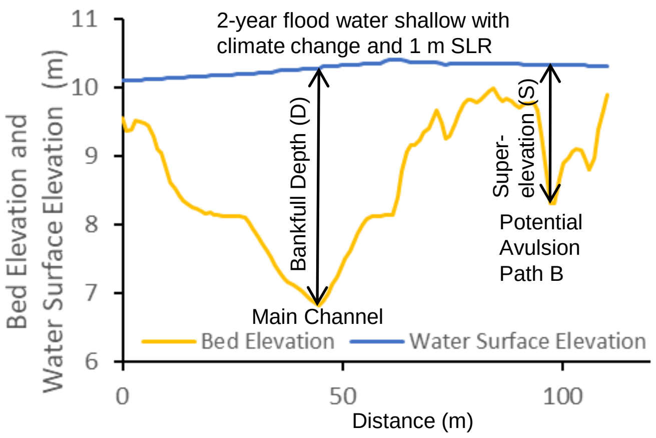
Avulsion Hazard Metrics

Super-elevation: describes the degree to which a channel is perched above the floodplain (see graph on right)

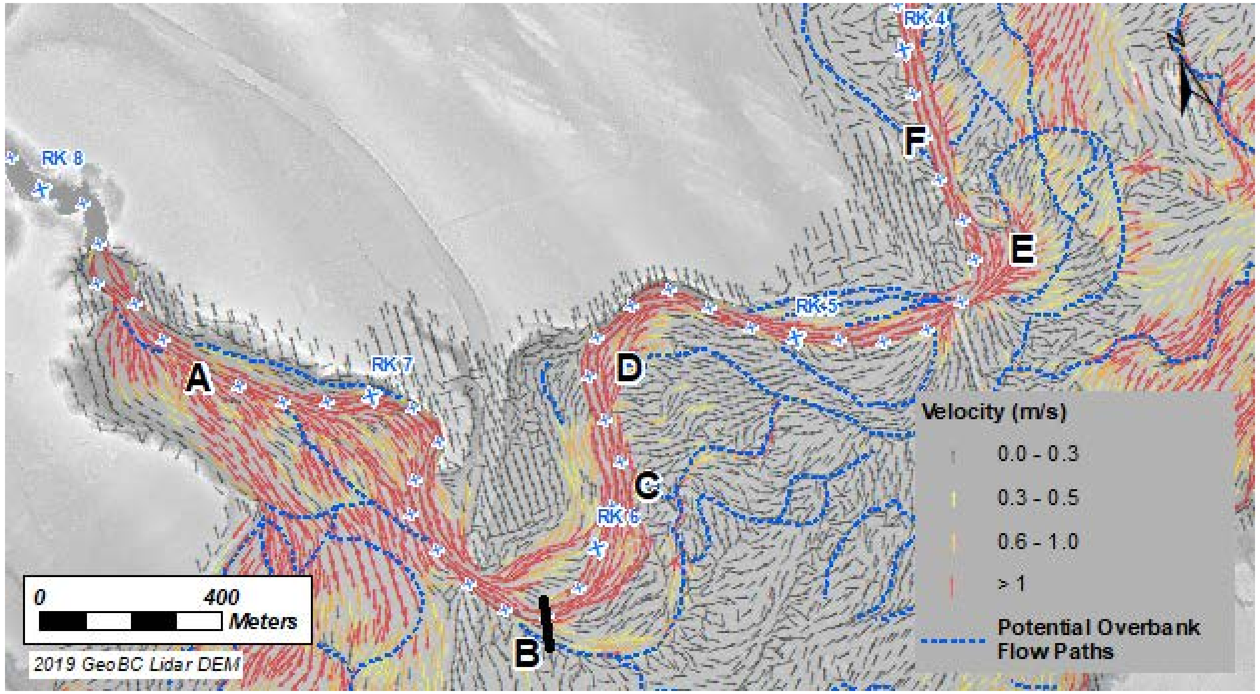
Normalized super-elevation: ratio of super-elevation to channel depth

Slope ratio: ratio of the slope of a possible avulsion path to the existing main channel slope

Example cross section plot showing super-elevation (S), bankfull depth (D), bed elevation, and water surface elevation for the 2-year flood with climate change and 1 m SLR. Cross section plot taken at avulsion node B (see map below for location). ▼



▶ Map showing select potential avulsion nodes (labelled A to E). 2D HEC-RAS hydraulic mode simulations of velocity vectors and rates (metres per second) for the design flood event and interpreted overbank flow paths are shown for context (blue paths).



10 GEOMORPHIC HAZARD MAPPING

Overview Level Mapping Information

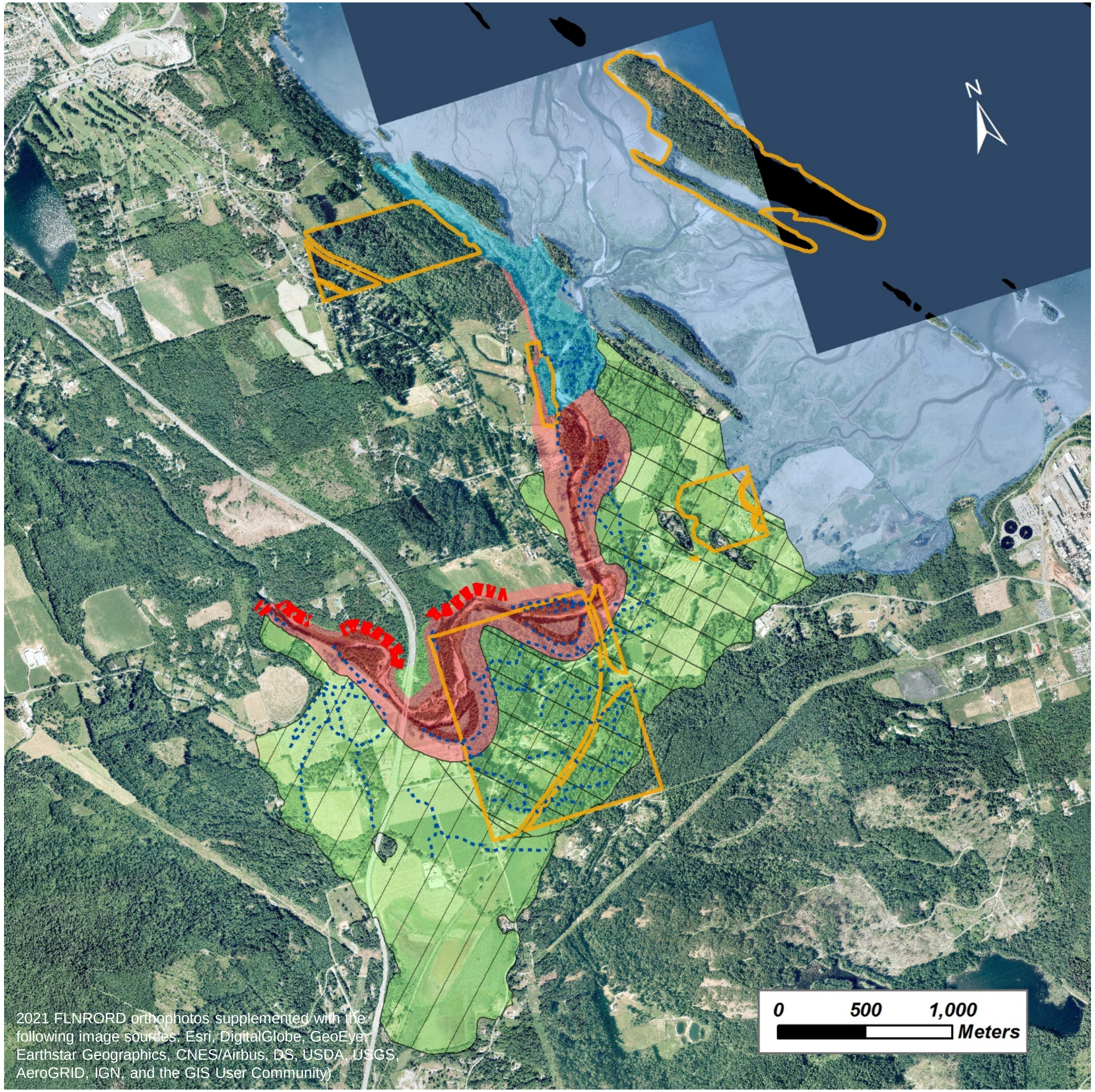
Legend

- First Nation Administrative Boundary
- Detected Relic Channel Paths
- Potential Geotechnical Hazard
- First Order Avulsion Hazard Zone
- Second Order Avulsion Hazard Zone
- Modern Valley Bottom
- Historical Migration Zone
- Erosion Hazard Area
- Distributary Hazard Zone
- Coastal Hazard Zone

The definitions for the hazard zones delineated in the geomorphic hazard map are provided on Page 37 and mapping criteria is described on Pages 38 to 43.

Potential geotechnical hazard defines an area with steep slopes within the erosion hazard zone or avulsion hazard zone, which may become geotechnically unstable due to inundation or erosion of the toe of the slope.

A geotechnical assessment is required to determine an appropriate geotechnical setback for land that may potentially be subject to any potential geotechnical hazards. Only steep slopes within 10 m of the erosion hazard zone boundary were flagged as potential geotechnical hazards. Additional steep slope hazards not flagged may exist outside of the erosion hazard zone.



▶ Geomorphic hazard map at the study area scale, showing the full extent of hazard mapping

11 REFERENCES

- Abbe, T.B., and Montgomery, D.R., 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. Regulated rivers: Research & Management, 12 (2-3), 201-221.
- APEGBC, 2017. Flood Mapping in BC, APEGBC Professional Practice Guidelines, V1.0. The Association of Professional Engineers and Geoscientists of British Columbia, Burnaby, BC, pp. 54.
- Ashmore, P., and Church, M., 2001. The Impact of Climate Change on River Processes in Canada. Geological Survey of Canada, Bulletin 555, pp. 58.
- Babakaiff S., 2000. BC Institute of Technology Stream Channel Protection Course Manual (EENG 8805). May 2000. BCIT Environmental Engineering. WPC #13266.1
- BC Housing 2019. BC Housing Design Guidelines and Construction Standards. British Columbia. Technical Bulletin No. 1-2020. https://www.bchousing.org/partner-services/asset-management-redevelopment/construction-standards
- Beechie, T.J., 2001. Empirical predictors of annual bed load travel distance, and implications for salmonid habitat restoration and protection. Earth Surf. Process. Landf. 26, 1025-1034.
- Bell, L.M. and Kallman, R.J. (1976). The Cowichan-Chemainus River Estuaries Status of Environmental Knowledge to 1975. Report of the Estuary Working Group Department of the Environment Regional Board Pacific Region. Special Estuary Series No. 4. Environment Canada.
- Church M., and Jakob M., 2020. What is a debris flood? *Water Resources Research*, 17.
- Cienciala P., Bernando M.M., Nelson, A.D., Haas, A.D. 2022. Interdecadal variation in sediment yield from a forested mountain basin: The role of hydroclimatic variability, anthropogenic disturbances, and geomorphic connectivity. Science of the Total Environment 826.
- Copper Canyon Commemorative Committee, 1990. 50 Years Logging at Copper Canyon 1940 – 1990. Chemainus Valley. Pacific Rim Artisan Village Foundation.
- Cluer, B., and Thorne, C., 2014. A stream evolution model integrating habitat and ecosystem benefits. River Research and Applications, 30, 135-154.
- DR Clough Consulting, 2007. Chemainus River Gravel Removal-Environmental Monitoring Report. For Halalt First Nation and District of North Cowichan.
- EGBC (2018). *Legislated Flood Assessments in a Changing Climate in BC, Version 2.1*. Engineers & Geoscientists British Columbia, Burnaby, BC. 192 pp.
- Forest Practices Board, 2004. Forest Practices Board Manual: Section 2 Standard Methods For Identifying Bankfull Channel Features and Channel Migration Zones. [online] Available from: http://www.dnr.wa.gov/Publications/fp_board_manual_section02.pdf
- Guthrie, R.H., 2005. Geomorphology of Vancouver Island: Mass Wasting Potential. B.C. Ministry of Environment, Victoria, BC. Research Report No. RR01., 24 pp.
- Halstead, E.C., 1966. Surficial geology of Duncan and Shawnigan map-areas, British Columbia. 92 B/13, 92 B/12 (East Half). Geological Survey of Canada, Department of Mines and Technical Surveys, Paper 65-24, pp. 3.
- Hodding, B.A. (1998). North Cowichan – A History in Photographs. The Corporation of the District of North Cowichan. Hignell Book Printing.
- Jerolmack, D.J., 2009. Conceptual framework for assessing the response of delta channel networks to Holocene sea level rise. Quaternary Science Reviews 28, 1786-1800.
- KWL, 2021. Chemainus River Geomorphology Scoping Study – Preliminary Geomorphic Assessment of Lower Chemainus River. Technical Memorandum (4202.001-300). Prepared by Kerr Wood Leidal Associates for Halalt First Nation. pp. 20.
- Legg., N.T. and Olsen, P.L., (2014). A Synthesis for Floodplain Management and Restoration. Washington Department of Ecology Shorelands and Environmental Assistance, Olympia, WA,
- Massey, N.W.D., and Friday, S.J., 1987. Geology of the Chemainus River-Duncan area, Vancouver Island* (92C/16; 92B/13). British Columbia Ministry of Energy, Mines and Petroleum Resources, 81-91.

11 REFERENCES

- MFLNRORD (2018). Flood Hazard Area Land Use Management Guidelines, originally Ministry of Water, Land and Air Protection, Province of British Columbia, May 2004, amended January 2018 by the Ministry of Forests, Lands, Natural Resource Operations and Rural Development (MFLNRORD). Ministry of Forests, Lands, Natural Resource Operations and Rural Development.
- Nanson, G.C. and Knighton, A.D. 1996. Anabranching Rivers: Their Cause, Character and Classification, Earth Surface Processes and Landforms. 21: 217-239.
- NHC (2015a). Lower Cowichan-Koksilah Floodplain Risk Mitigation and Management Program. Sediment Management Plan – Final Report. (300030). Report prepared by Northwest Hydraulic Consultants for Cowichan Valley Regional District. Cowichan Valley Regional District.
- NHC (2015b). Lower Nooksack River Project Alternatives Analysis Geomorphic Characterization. Final Report (200088). Report prepared by Northwest Hydraulic Consultants for Whatcom County, Washington State and the Watershed Company on behalf of Whatcom County Flood Control Zone District.
- Obedkoff, W., 2003. Streamflow in the Lower Mainland and Vancouver Island. Ministry of Sustainable Resource Management, Aquatic Information Branch, pp. 186.
- Olsen, P.L., Legg., N.T., Abbe, T.B., Reinhart, M., and Radloff, J.K., (2014). A methodology for delineating planning-level channel migration zones. Washington Department of Ecology Shorelands and Environmental Assistance, Olympia, WA, pp. 71.
- Olsen, W.H. (1981). Water over the wheel. Chemainus Crofton and District Chamber of Commerce.
- Pike R.G., Redding R.E., Moore R.D., Winkler R.D., and Bladon K. D., (editors). 2010. Compendium of Forest Hydrology and Geomorphology in British Columbia. Volume 1 of 2. B.C. Min. For. Range For. Sci. Prog., Victoria, B.C. and FORREX Forum for Research and Extension in Natural Resources, Kamloops, B.C. Land Manag. Handb. 66. https://www.for.gov.bc.ca/hfd/pubs/Docs/Lmh/Lmh66.htm
- Rapp, C.F., Abbe, T.B. 2003. A Framework for Delineating Channel Migration Zones. Final Draft. Washington State Department of Transportation. November 2003.
- Richards KS, Brasington J, Hughes F. 2002. Geomorphic dynamics of floodplains: ecological implications and a potential modelling strategy. *Freshwater Biology* 47: 559-579.
- Rozen D.L. 19085. Place-names of the Island Halkomelem Indian People. B.A. Masters Thesis, Department of Antrhopology and Sociology, University of British Columbia, 1972.
- Schumm, S.A., 1993. River response to baselevel change: implications for sequence stratigraphy. J. Geol. 101, 279-294.
- Sidle, R.C., Pearce, A.J., O'Loughlin C.L., 1985. Hillslope stability and land use. American Geophysical Union. Water Resources Monograph Series 11.
- Steiger J., Tabacchi E., Dufour S., Corneblit D., Peiry, J.-L. 2005. Hydrogeomorphic processes affecting riparian habitat within alluvial channel-floodplain river systems: a review for the temperate zone. *River Res. Applic.* 21: 719-737.
- Turner, R.D (1973). Vancouver Island Railroads. Golden West Books.
- U.S. Army Corps of Engineers, 1994. Channel Stability Assessment for Flood Control Projects (1110 2-1418). Engineering Manual. Washington, DC, pp. 117.
- USGS, 2008. Simulations of Flow, Sediment Transport, and Sediment Mobility in the Lower Coeur d'Alene River, Idaho (2008-5093). Scientific Investigations Report. Prepared in cooperation with the Idaho Department of Environmental Quality, Basin Environmental Improvement Commission, and the U.S. Environmental Protection Agency, Virginia, pp. 164.
- Wilford, D.J., Sakals, M.E., Innes, J.L., Sidle, R.C., and Bergerud, W.A., 2004. Recognition of debris flow, debris flood and flood hazard through watershed morphometrics. Landslides, 1, 61-66
- Winkler, R., Moore, R., Redding, T., Spittlehouse, D., Smerdon, B., and Carlyle-Moses, D. (2010). The Effects of Forest Disturbance on Hydrologic Processes and Watershed Response. Compendium of forest hydrology and geomorphology in British Columbia. BC Min. For. Range, 66, 179.
- Wolman, M.G., and Miller, J.P., Magnitude and Frequency of forces in geomorphic processes. The Journal of Geology, 68 (1), pp. 54-74.
- Yorath, C.J., and Nasmith, H.W., 1995. The geology of Vancouver Island: a field guide. Orca, Victoria, BC, pp. 172.